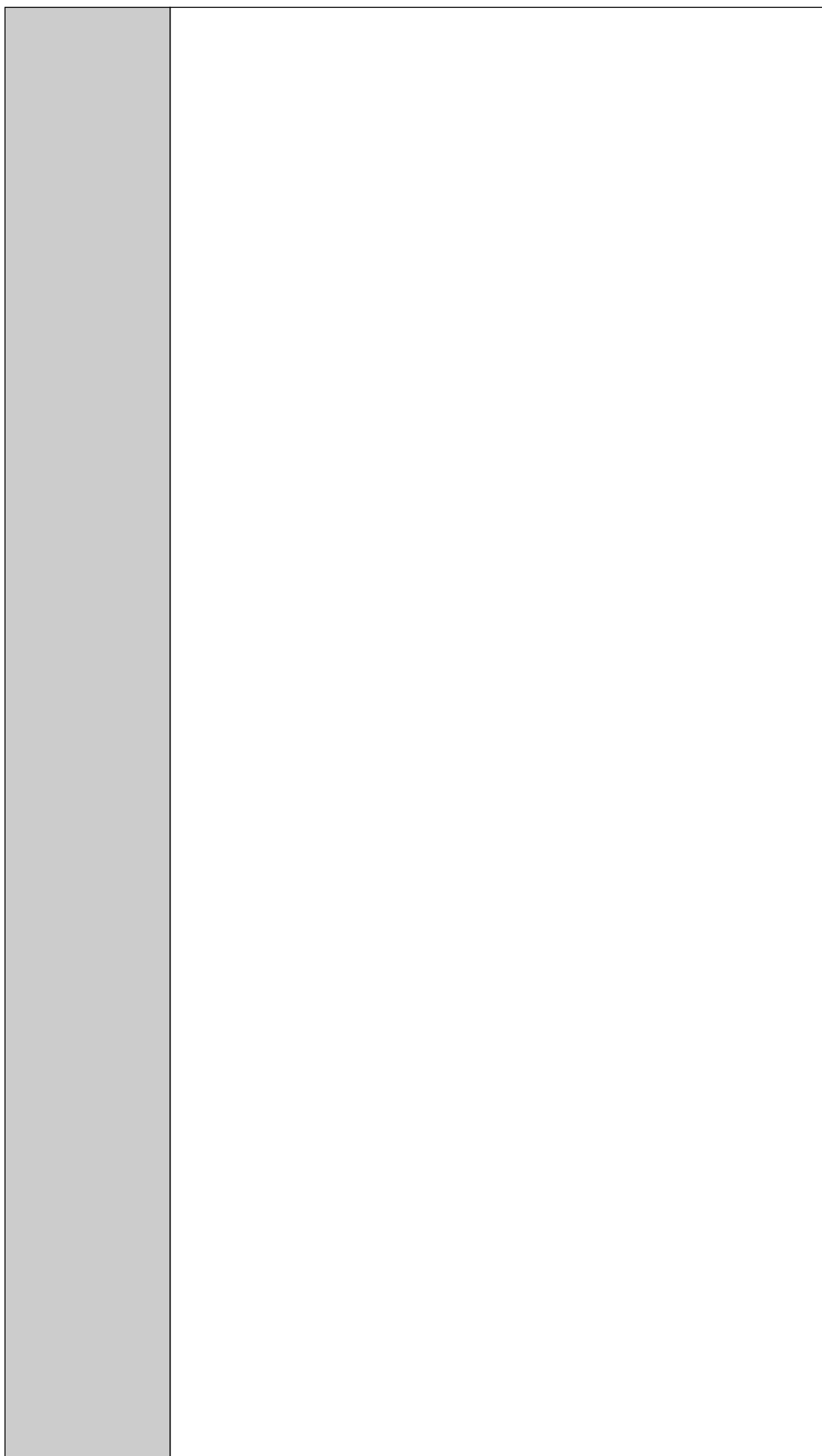


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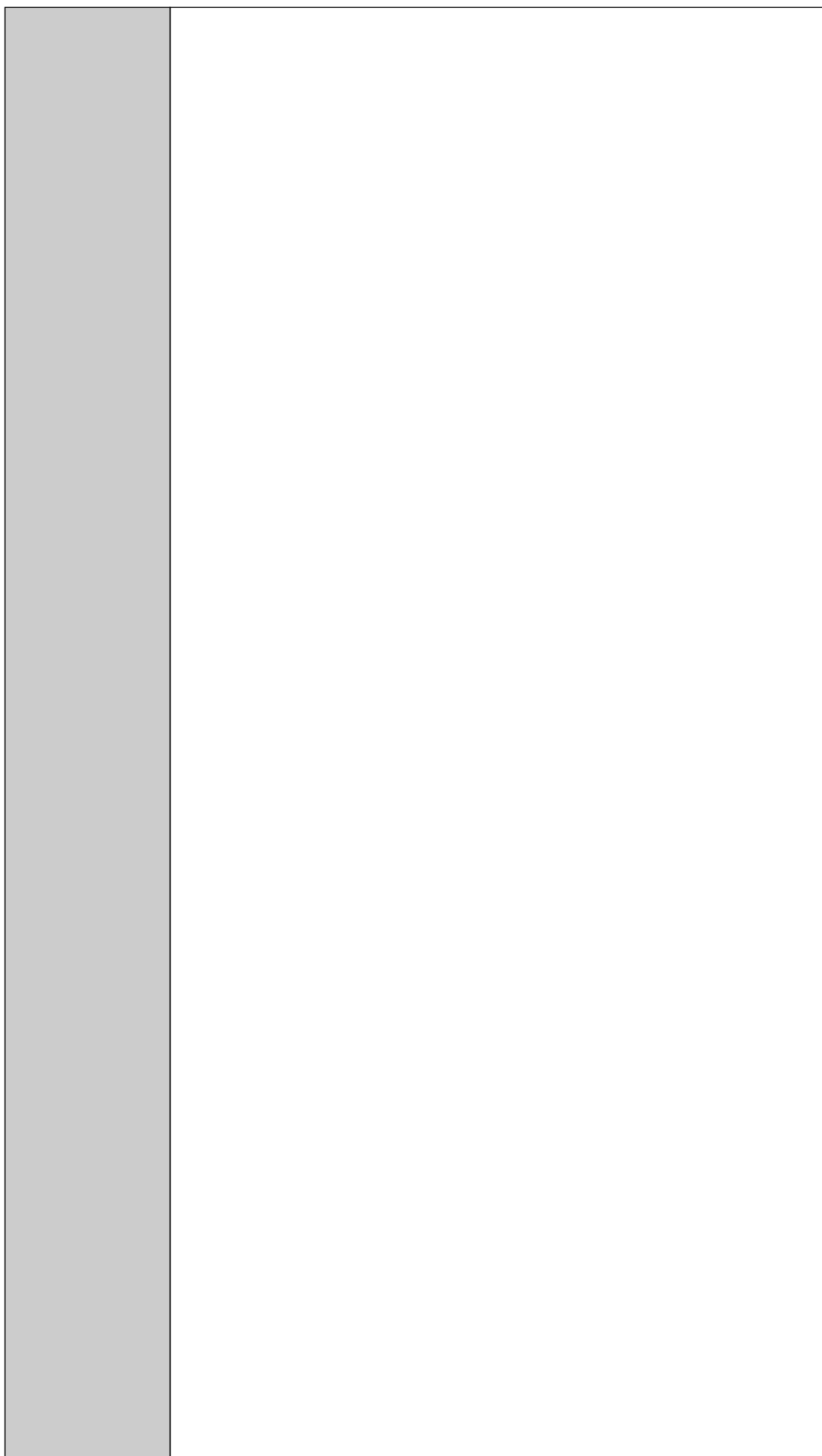
Title	Enrichment of package antenna approach with dual feeds, guard ring, and fences of vias
Author(s)	Zhang, Yue Ping
Citation	Zhang, Y. P. (2009). Enrichment of Package Antenna Approach With Dual Feeds, Guard Ring, and Fences of Vias. IEEE Transactions On Advanced Packaging. 32(3), 612-618.
Date	2009
URL	http://hdl.handle.net/10220/6240

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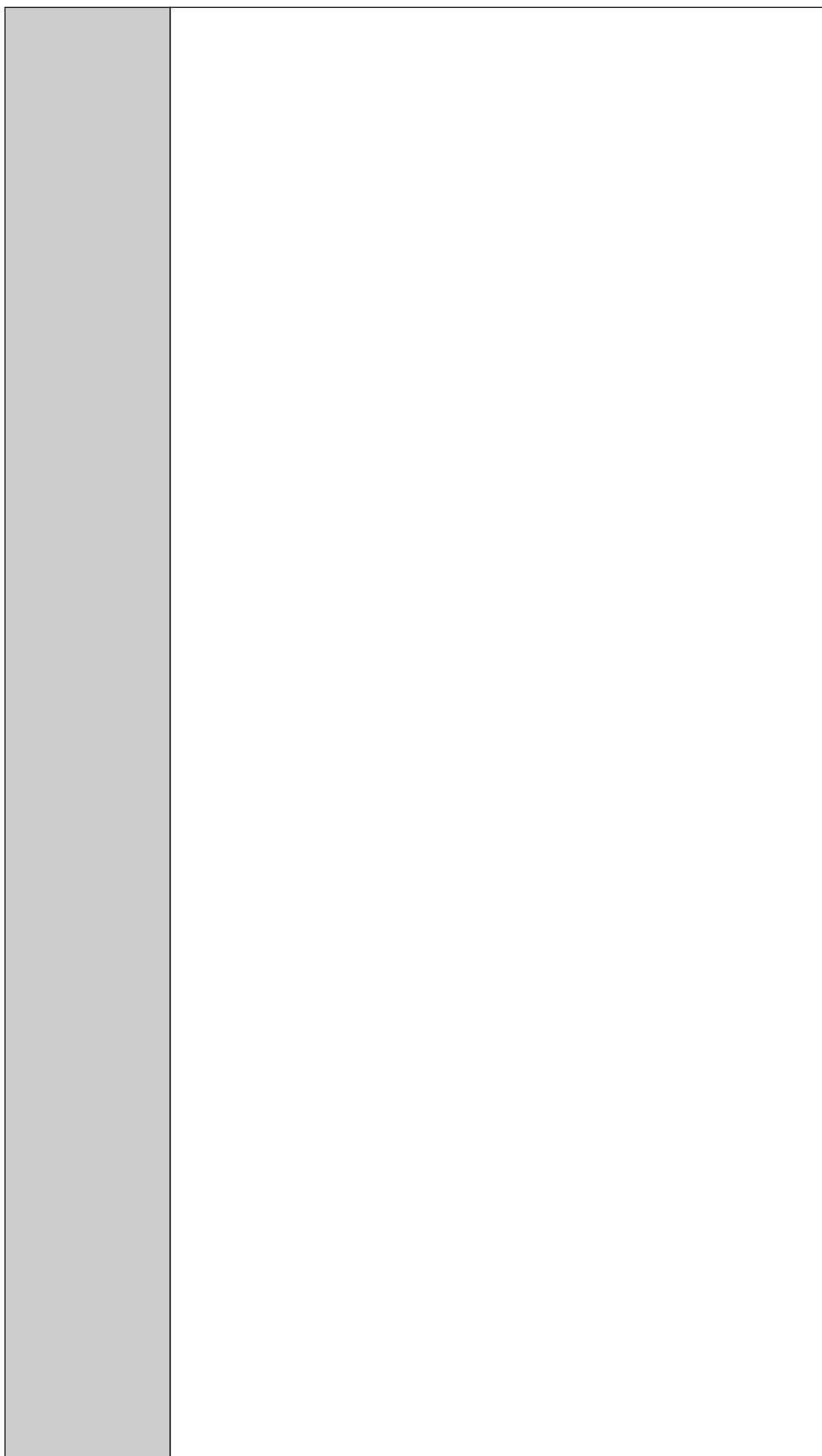
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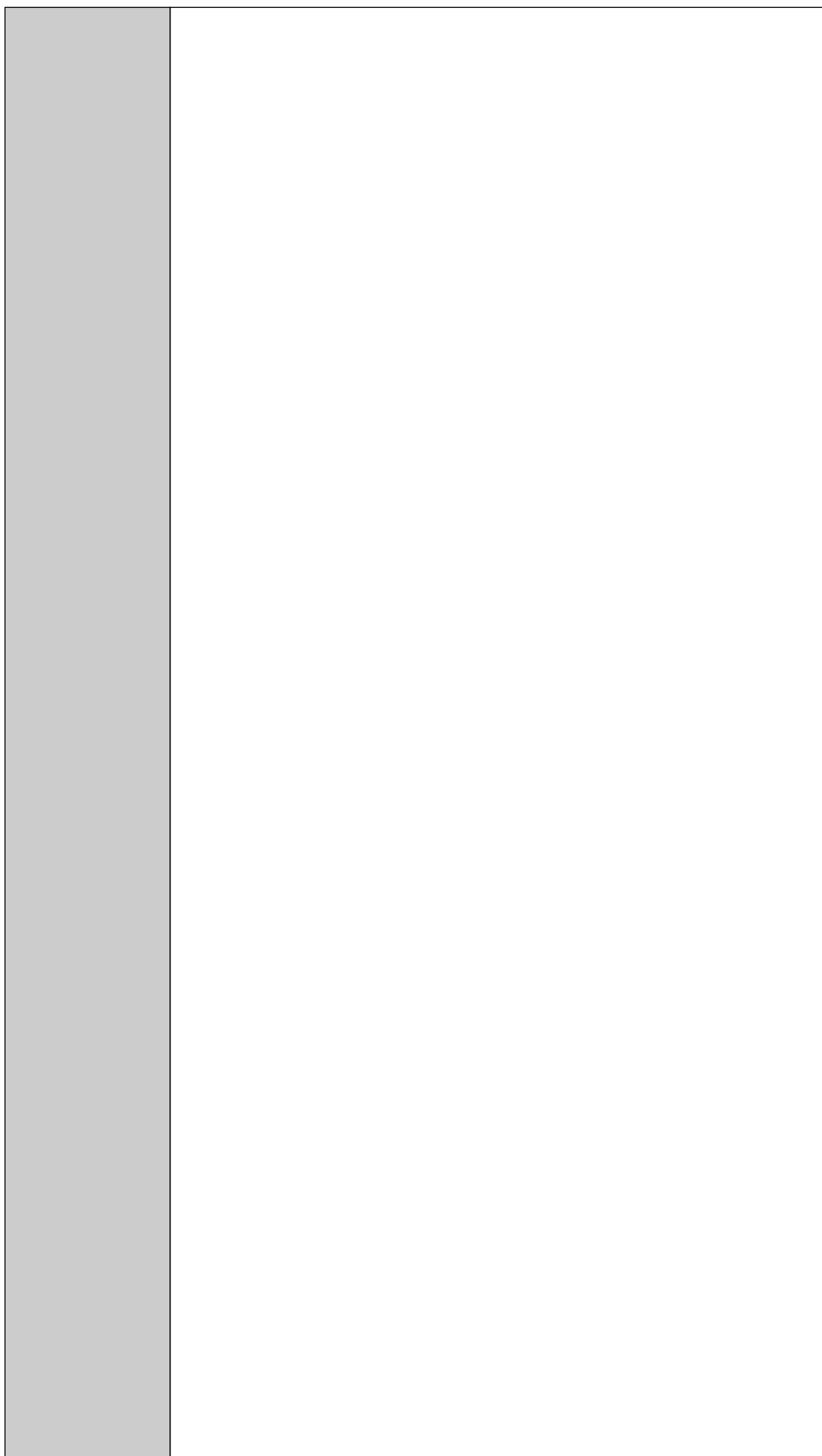
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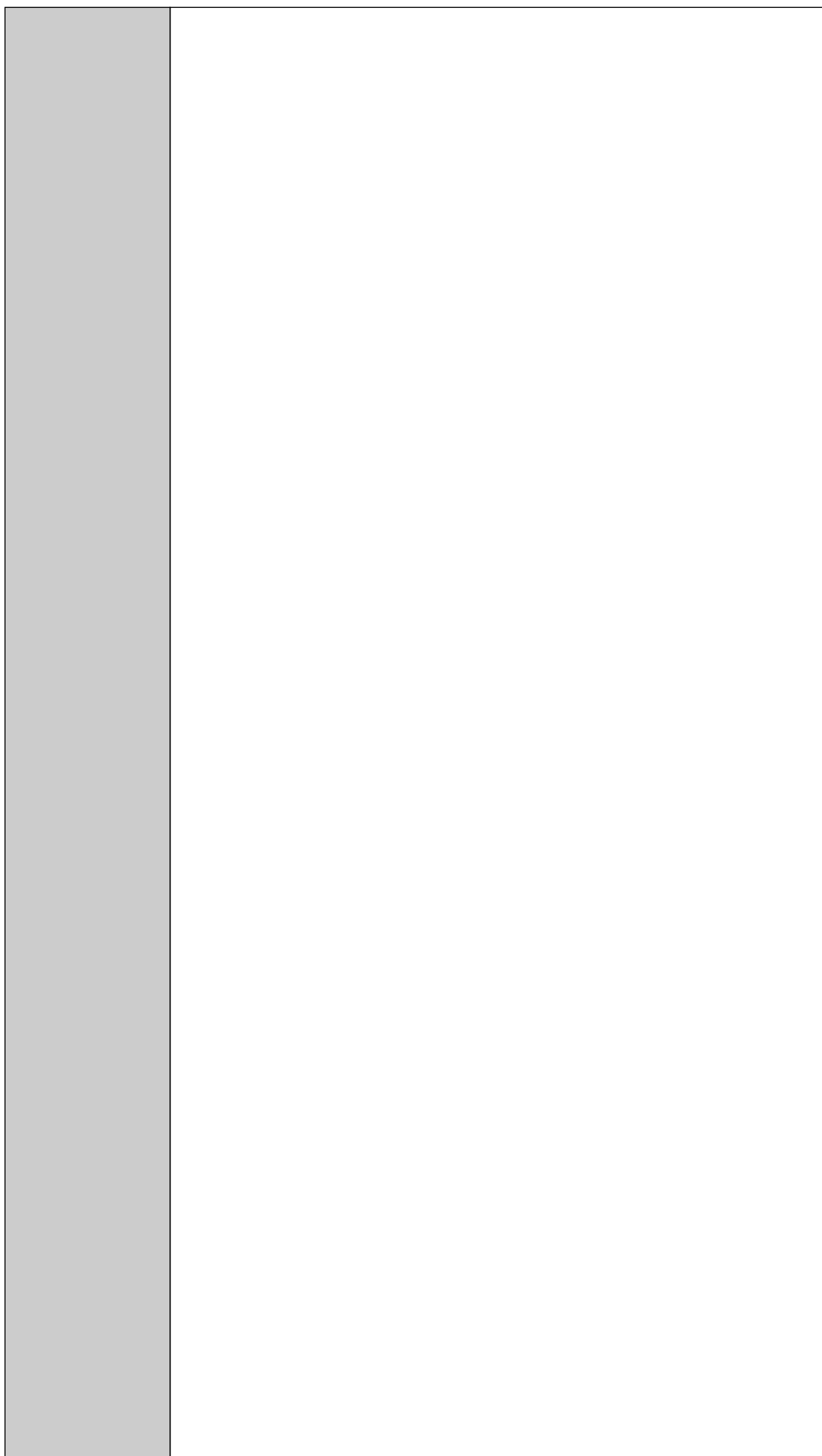
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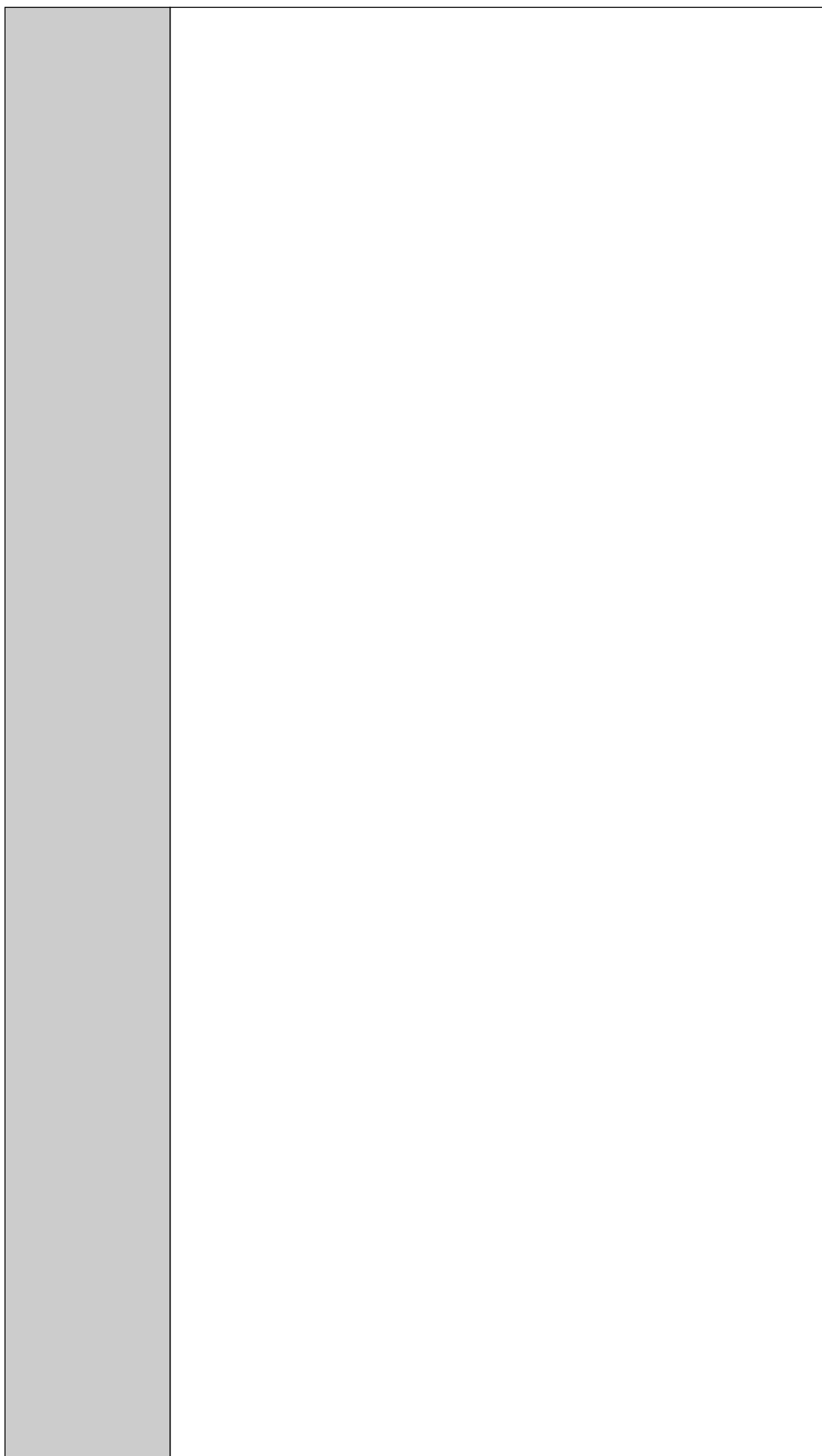
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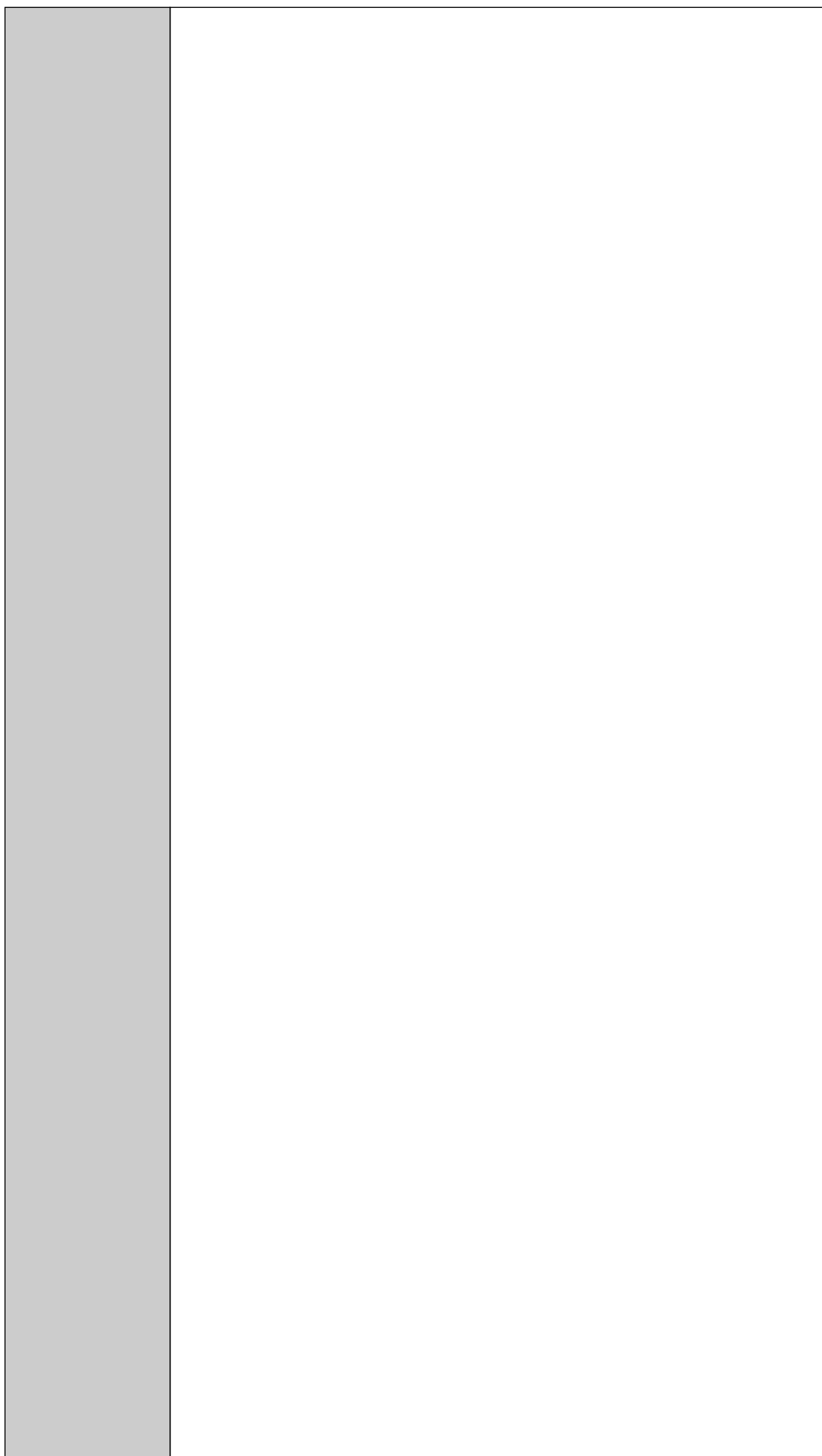
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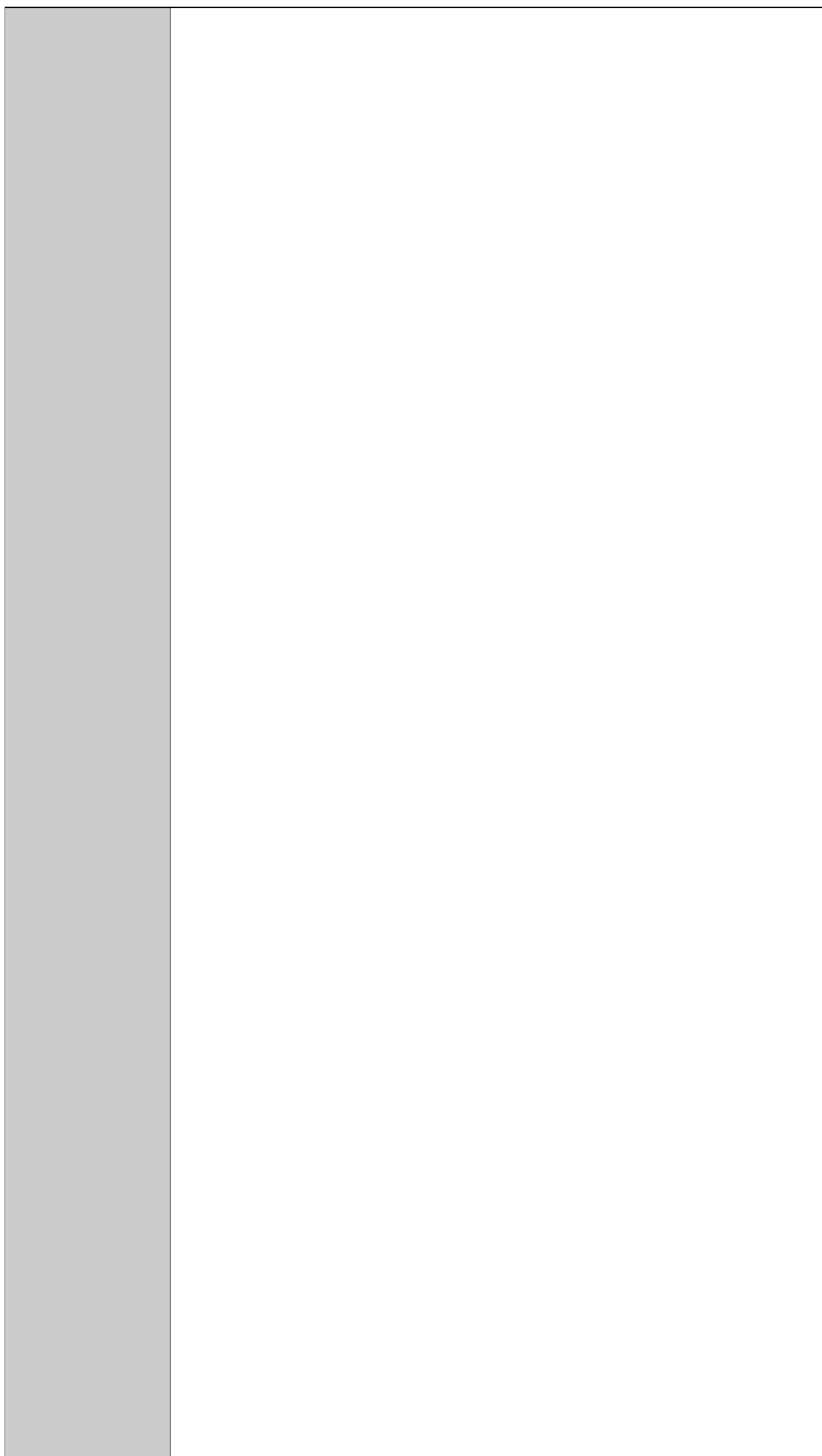
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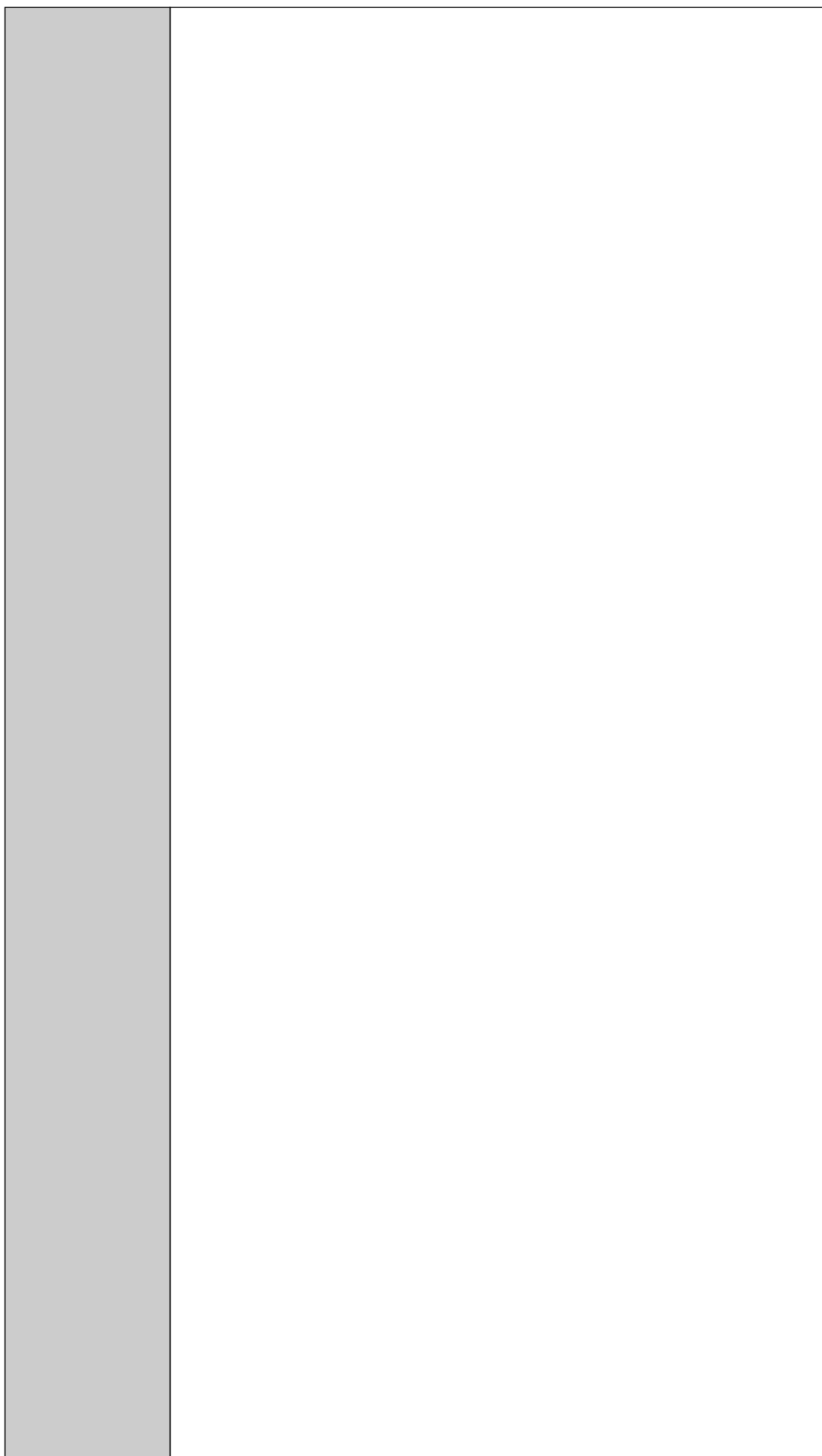
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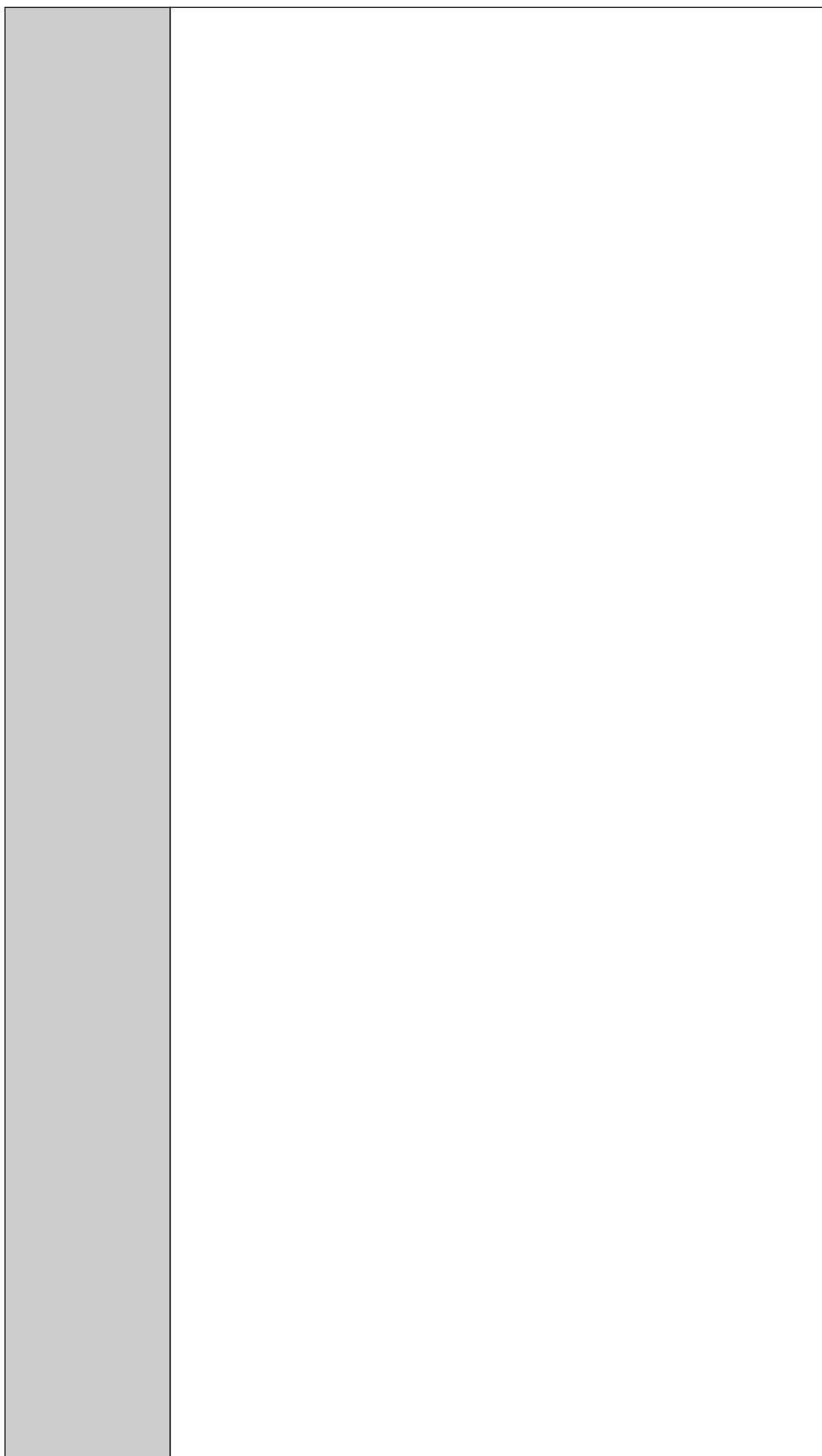
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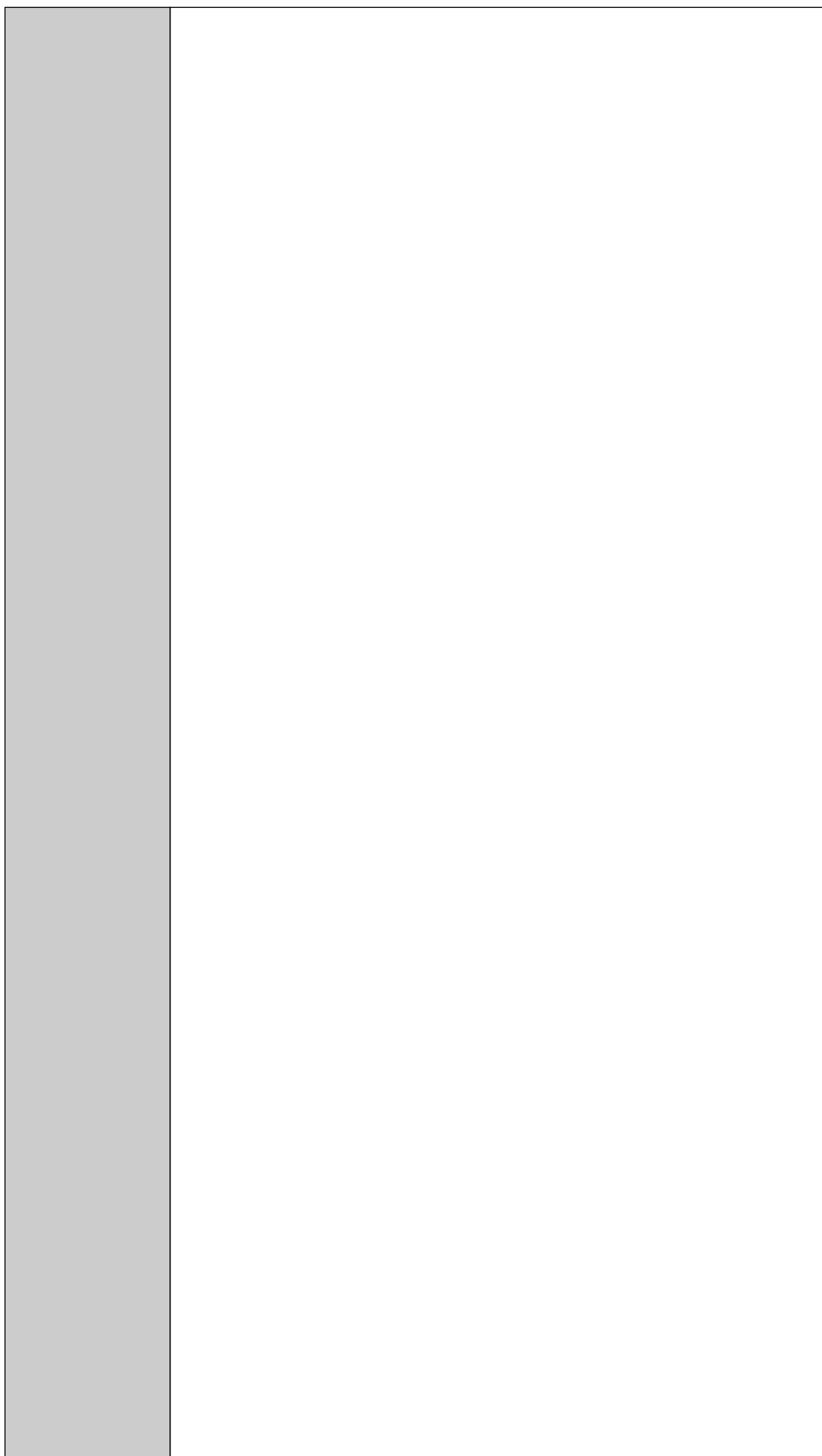
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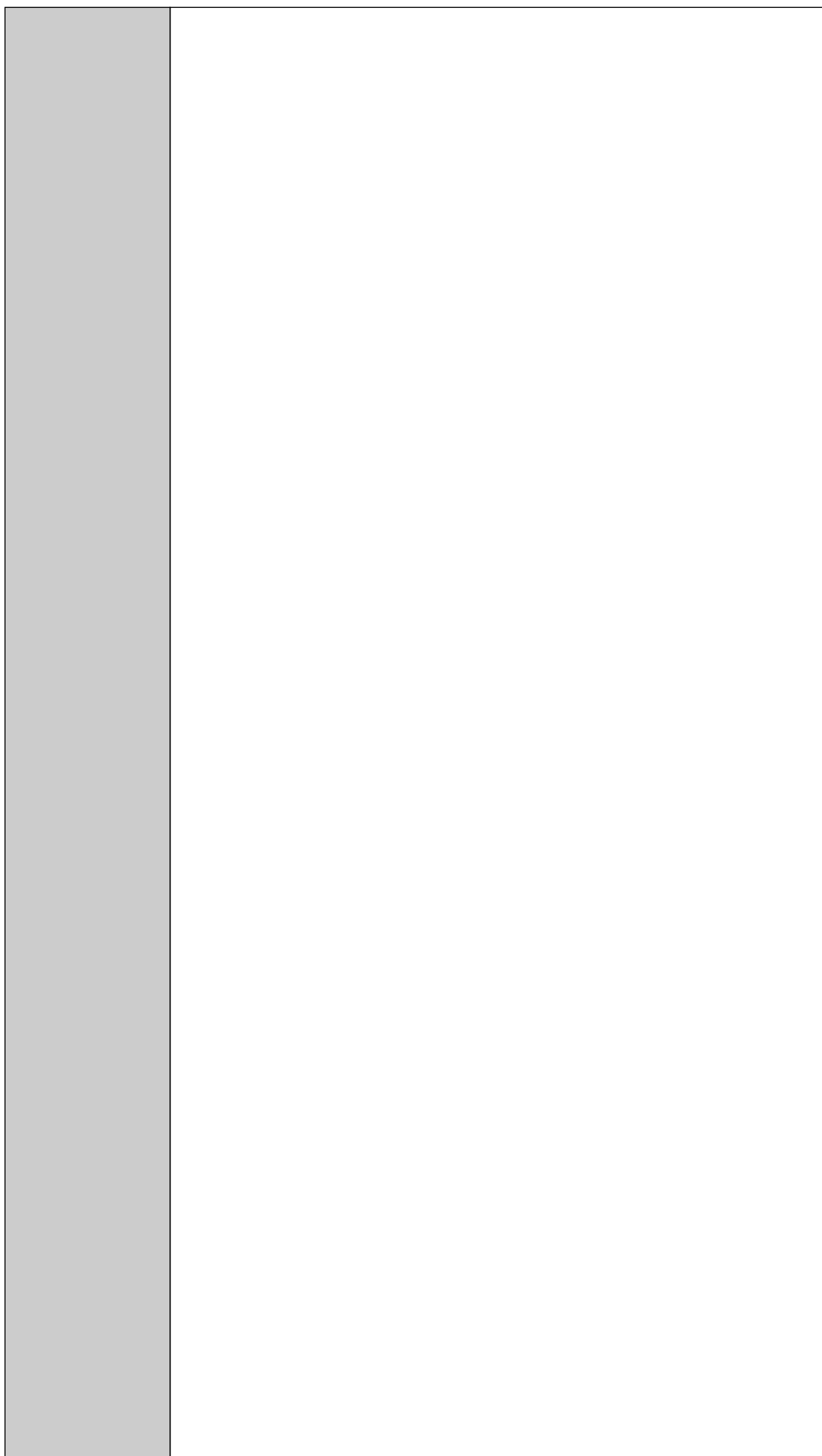
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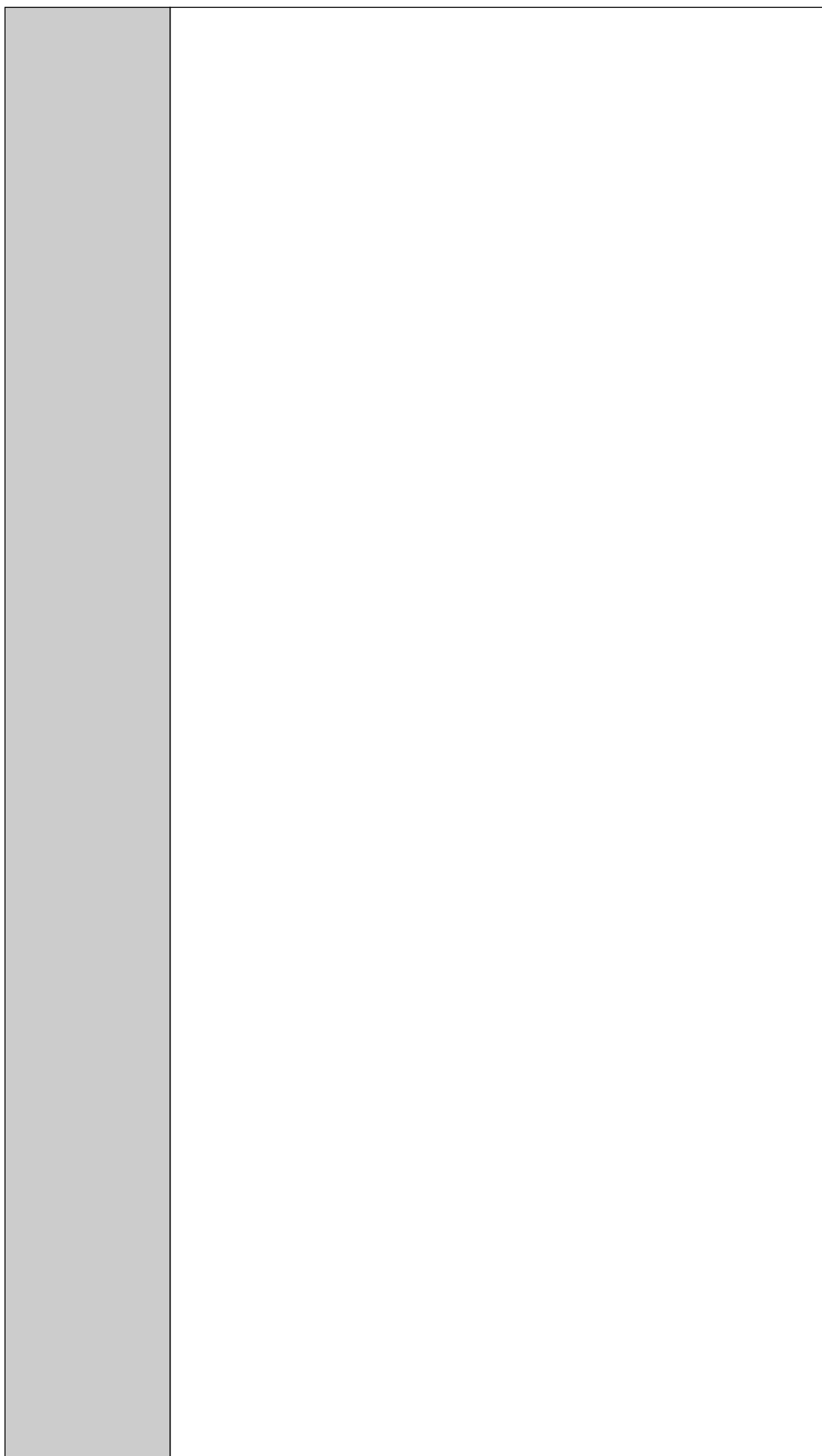
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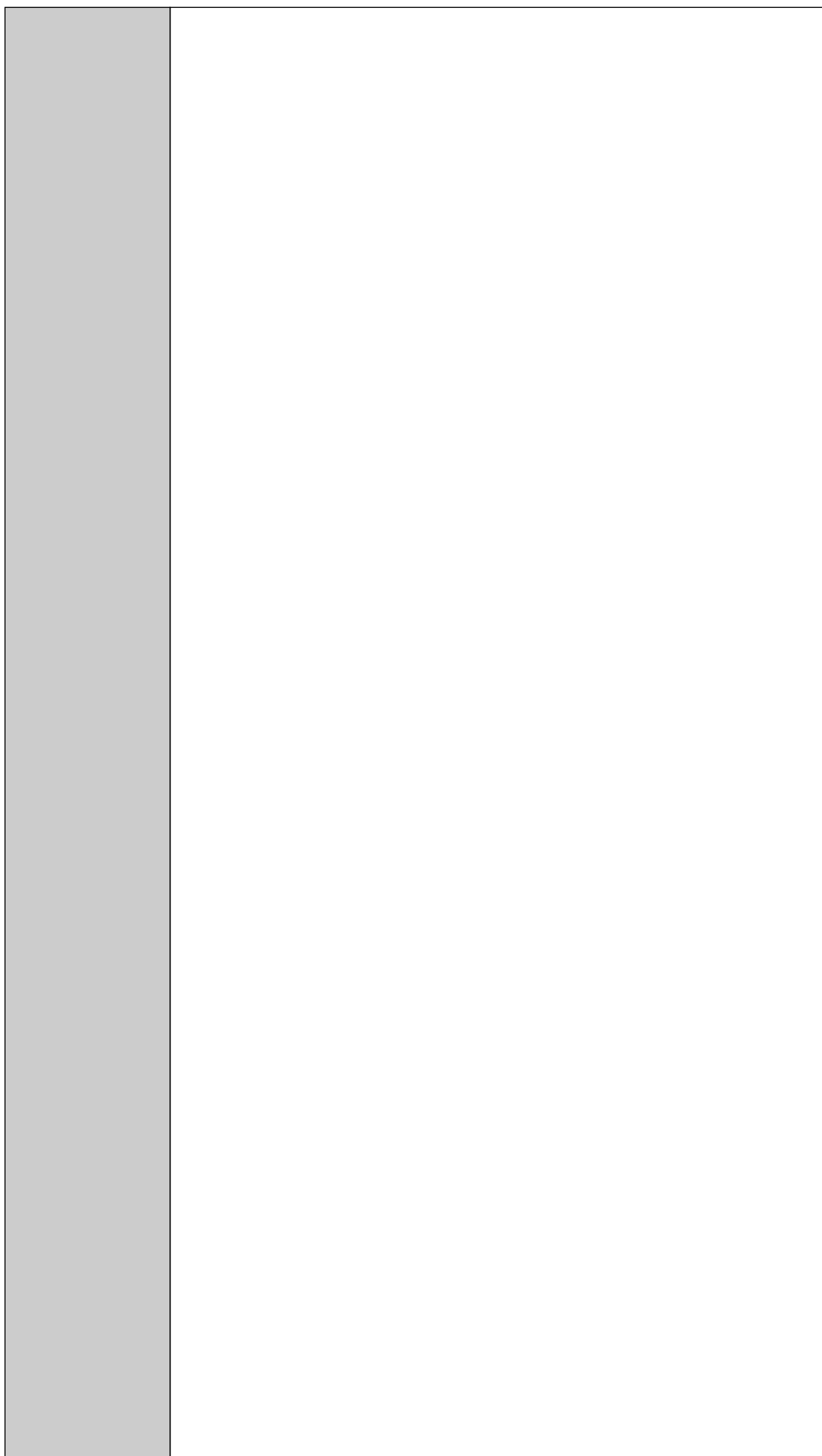
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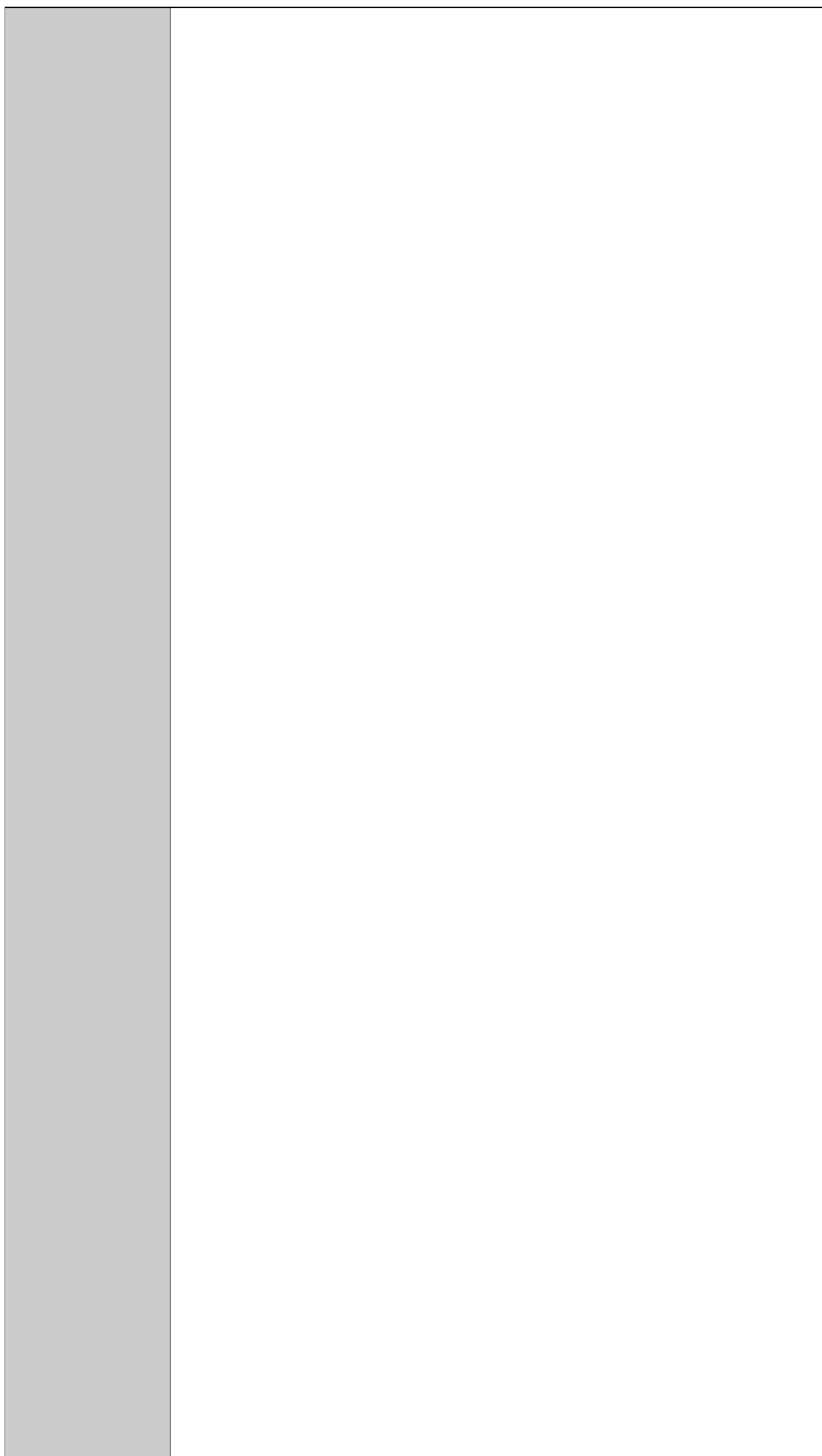
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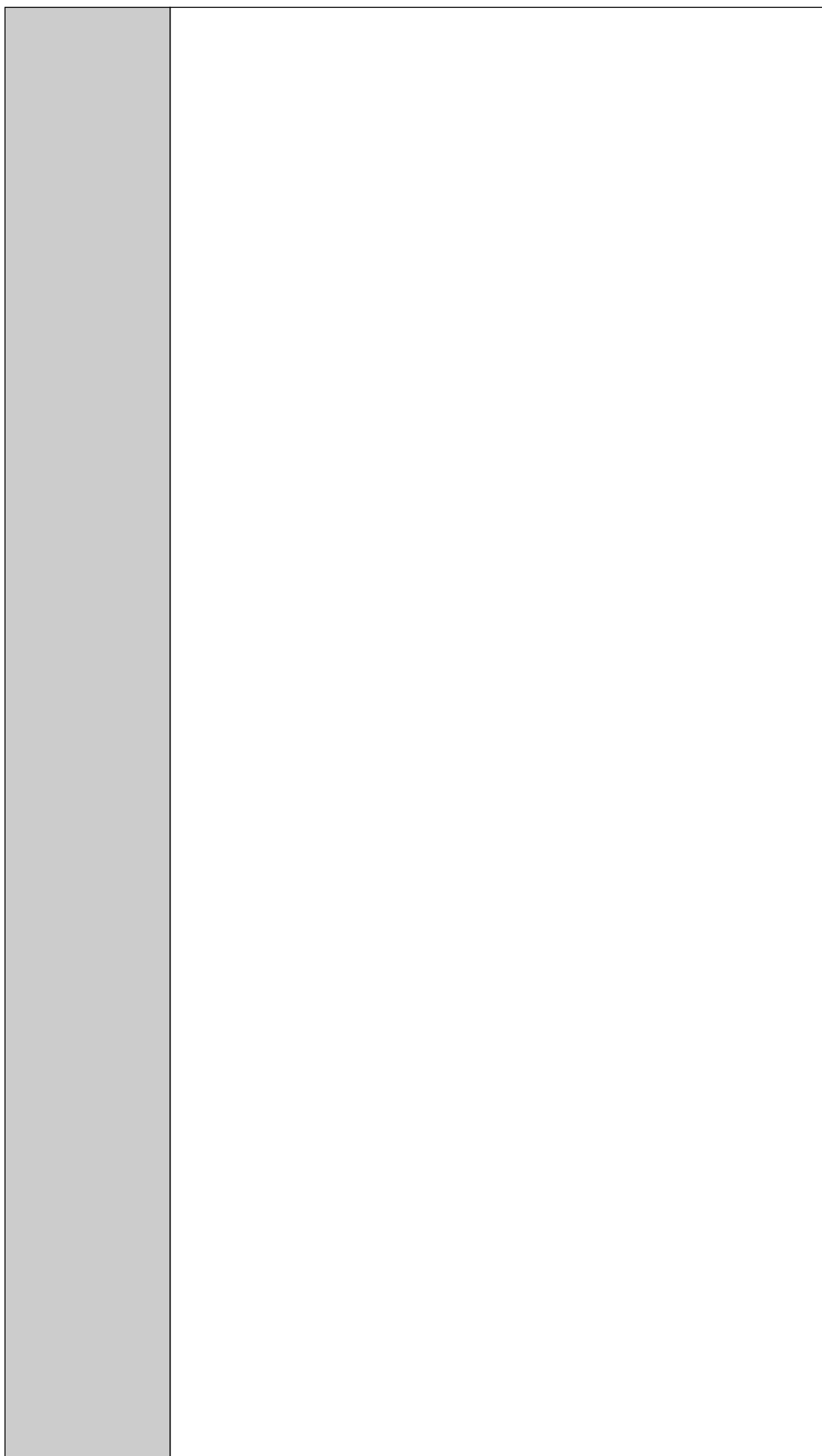
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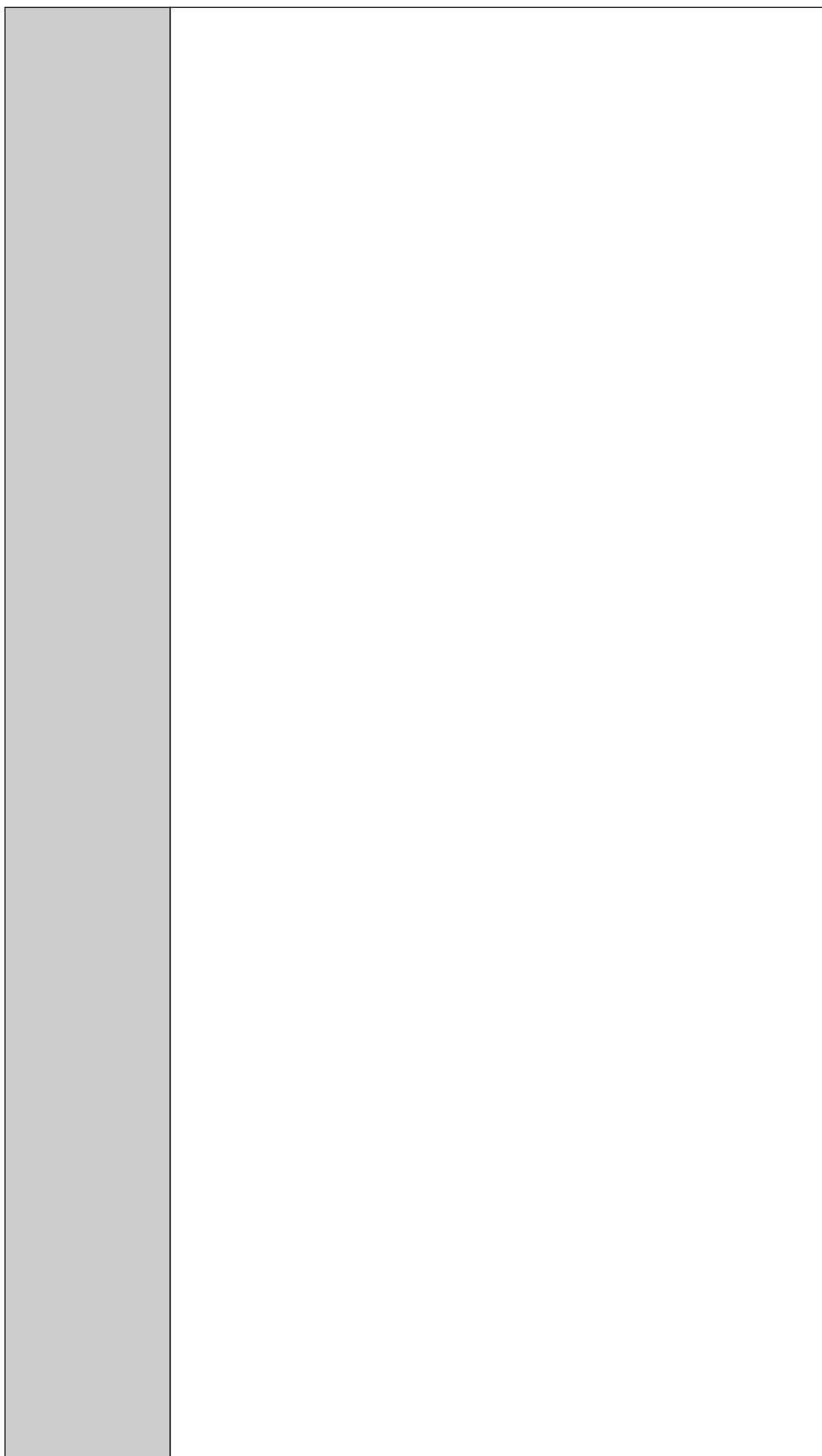
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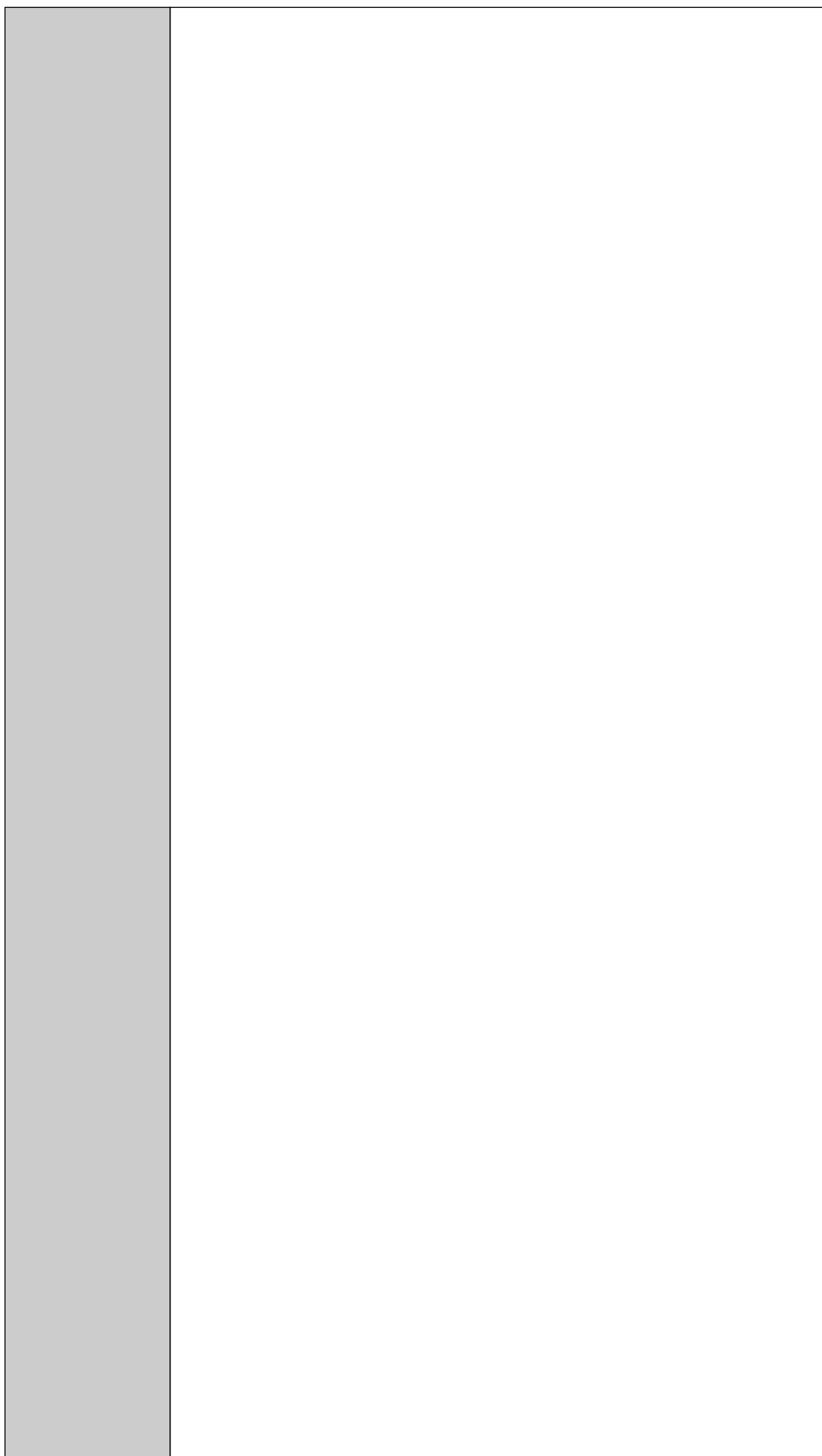
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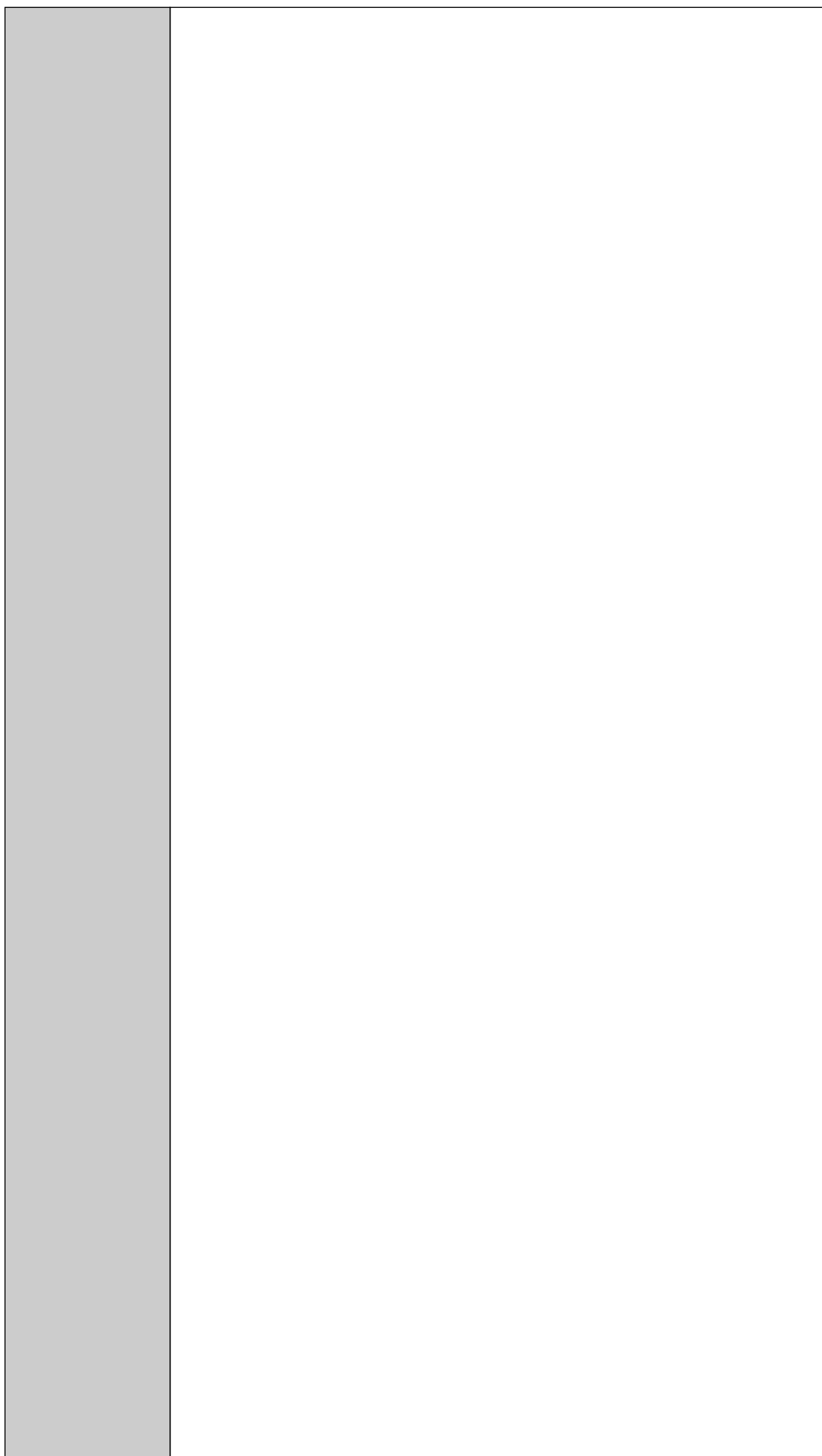
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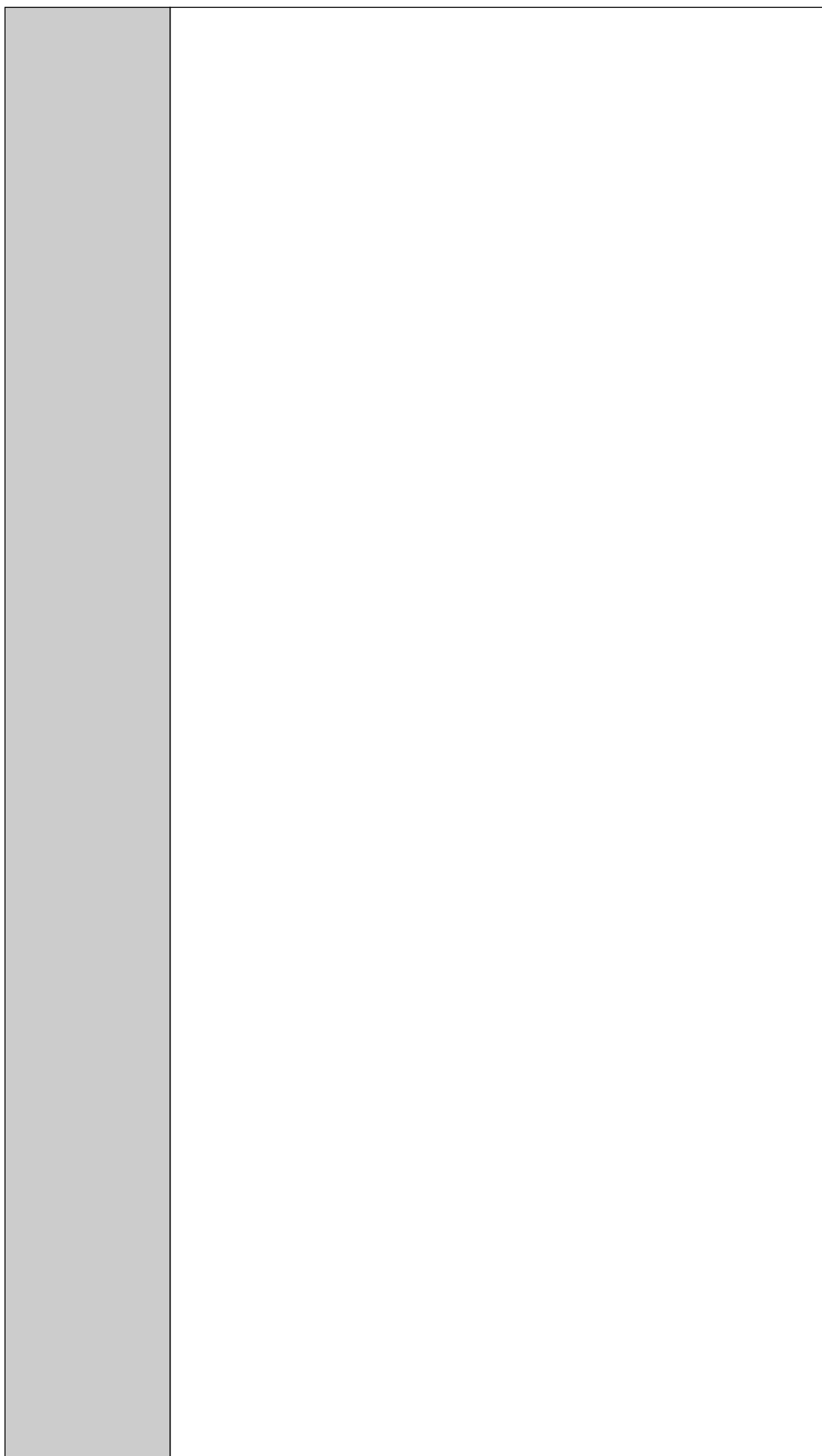
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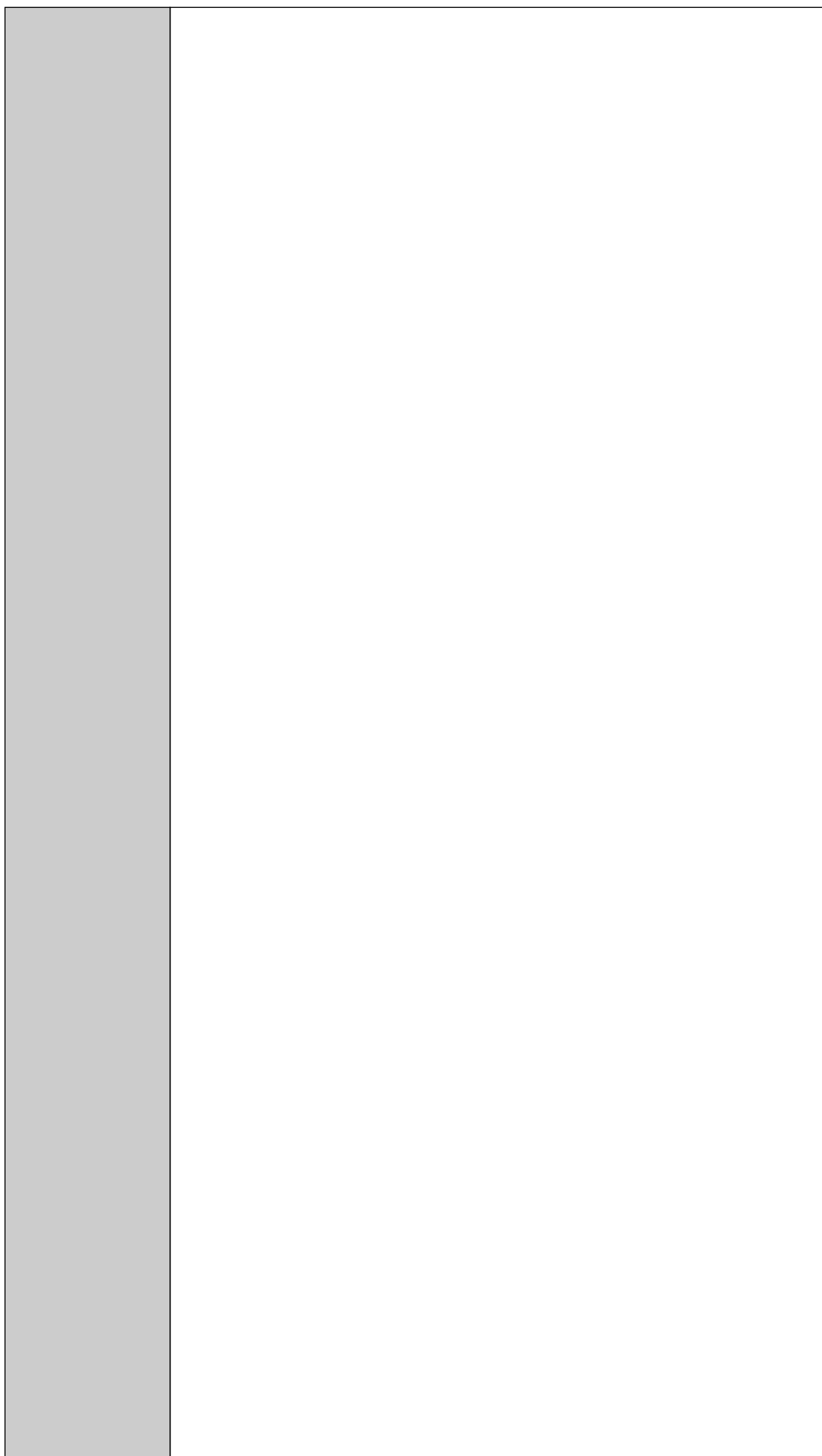
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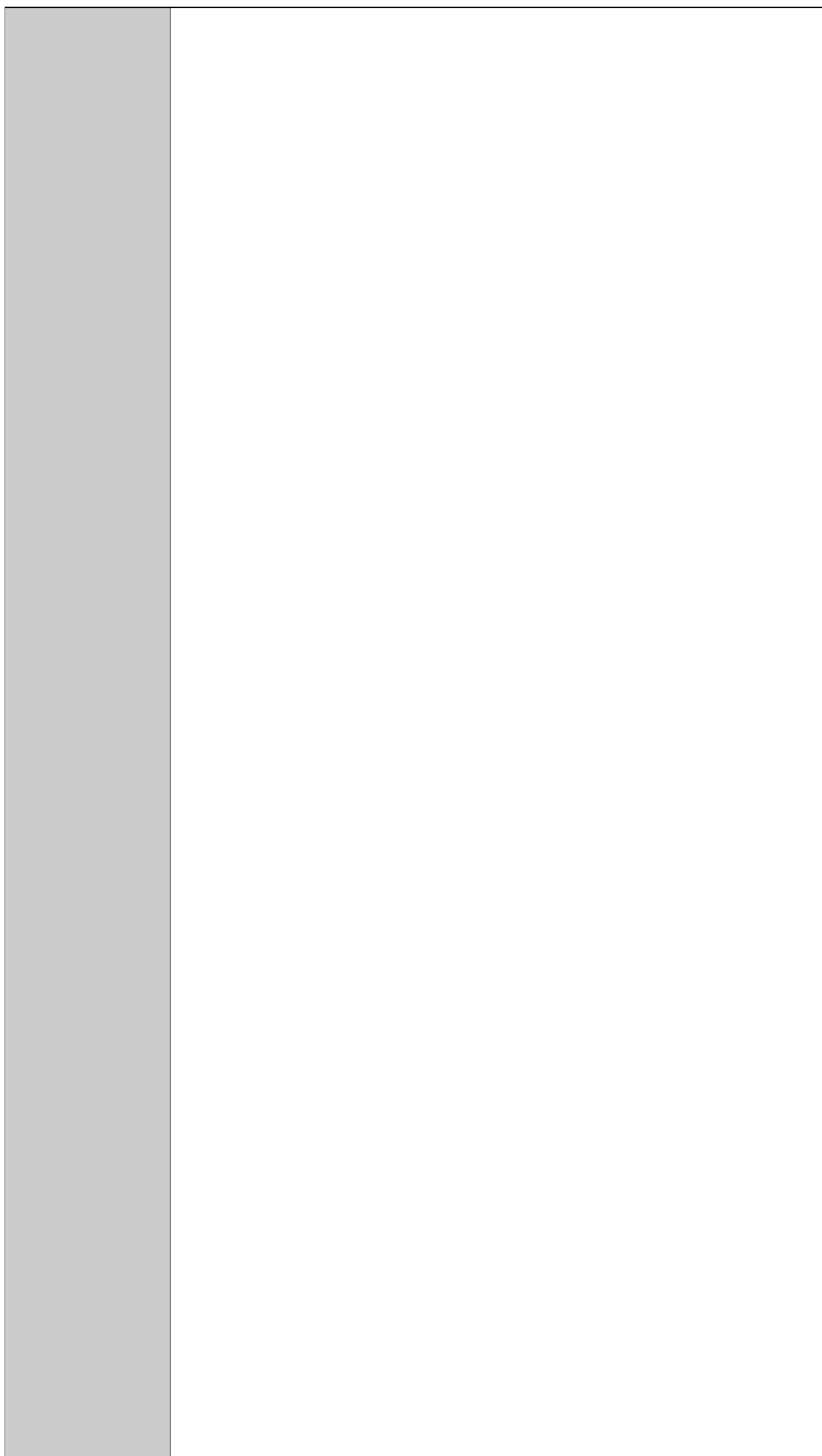
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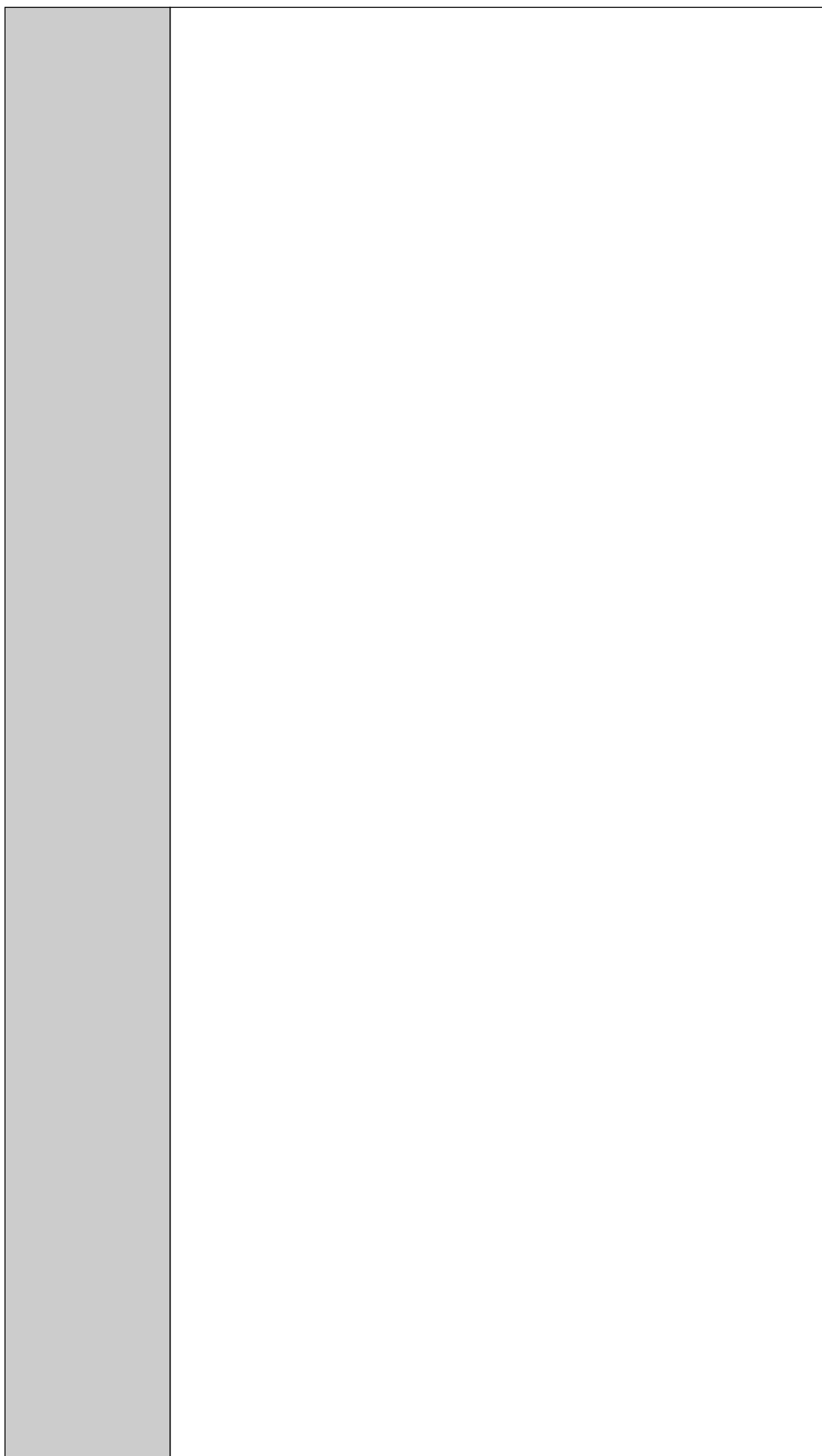
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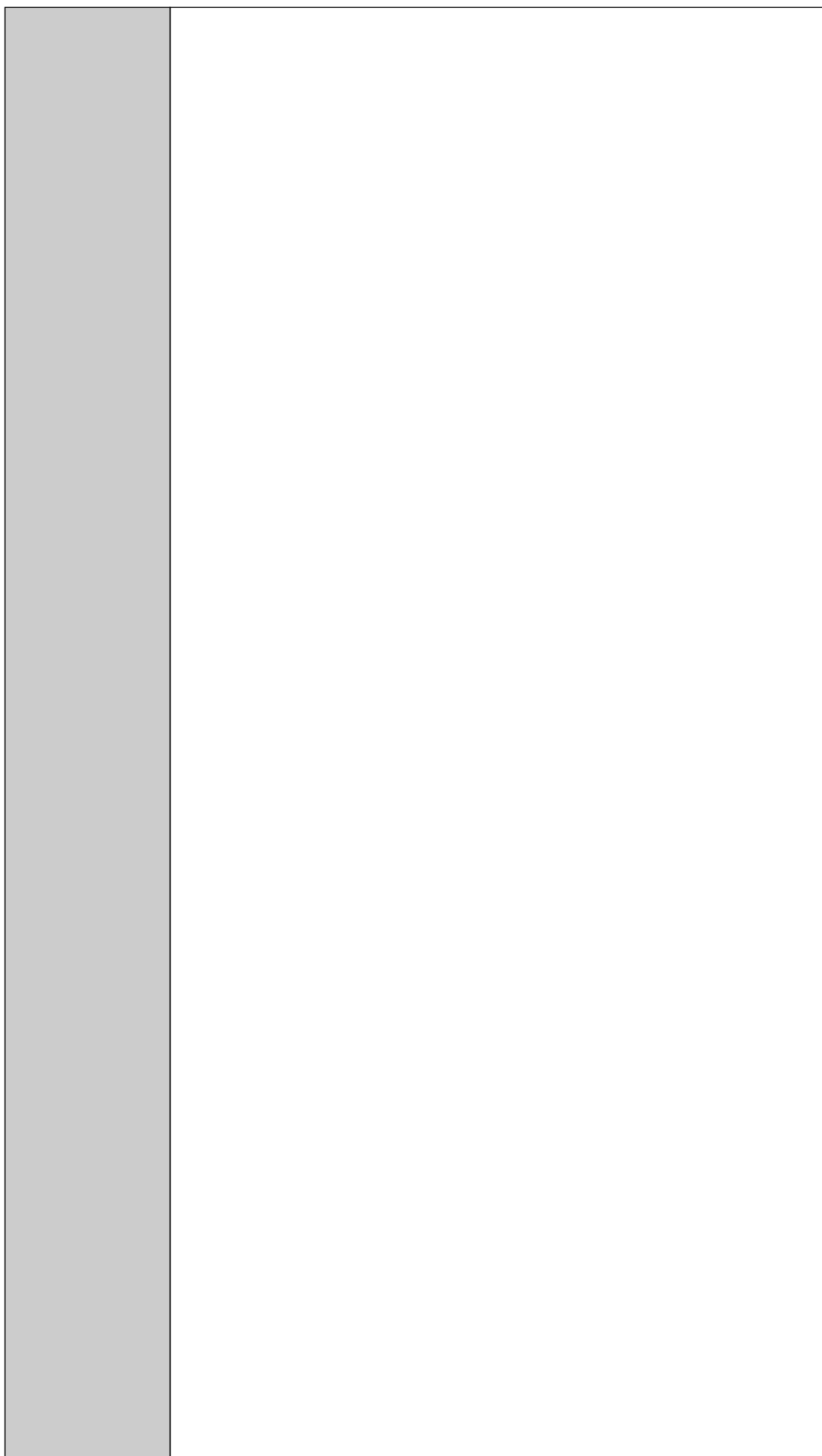
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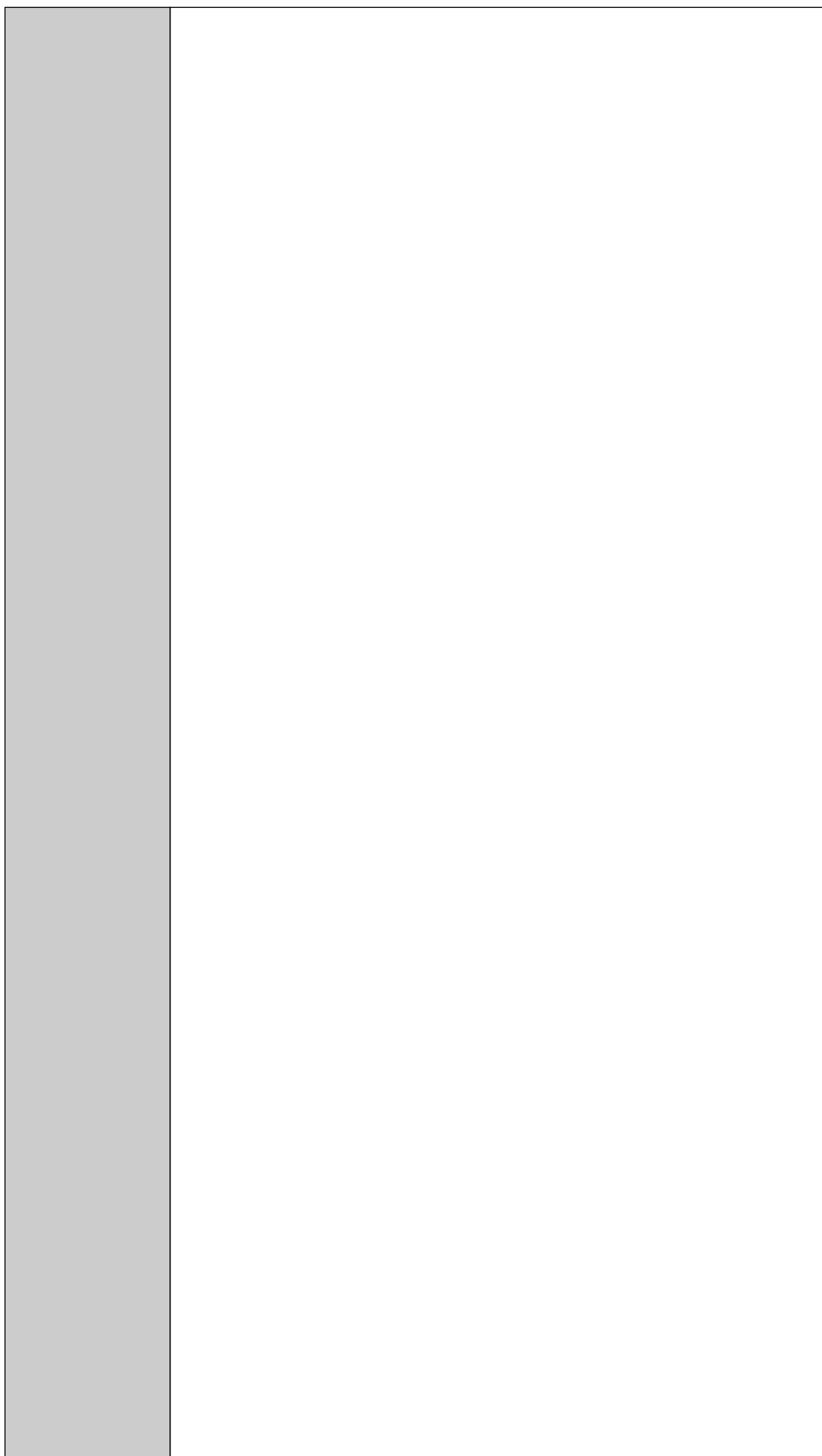
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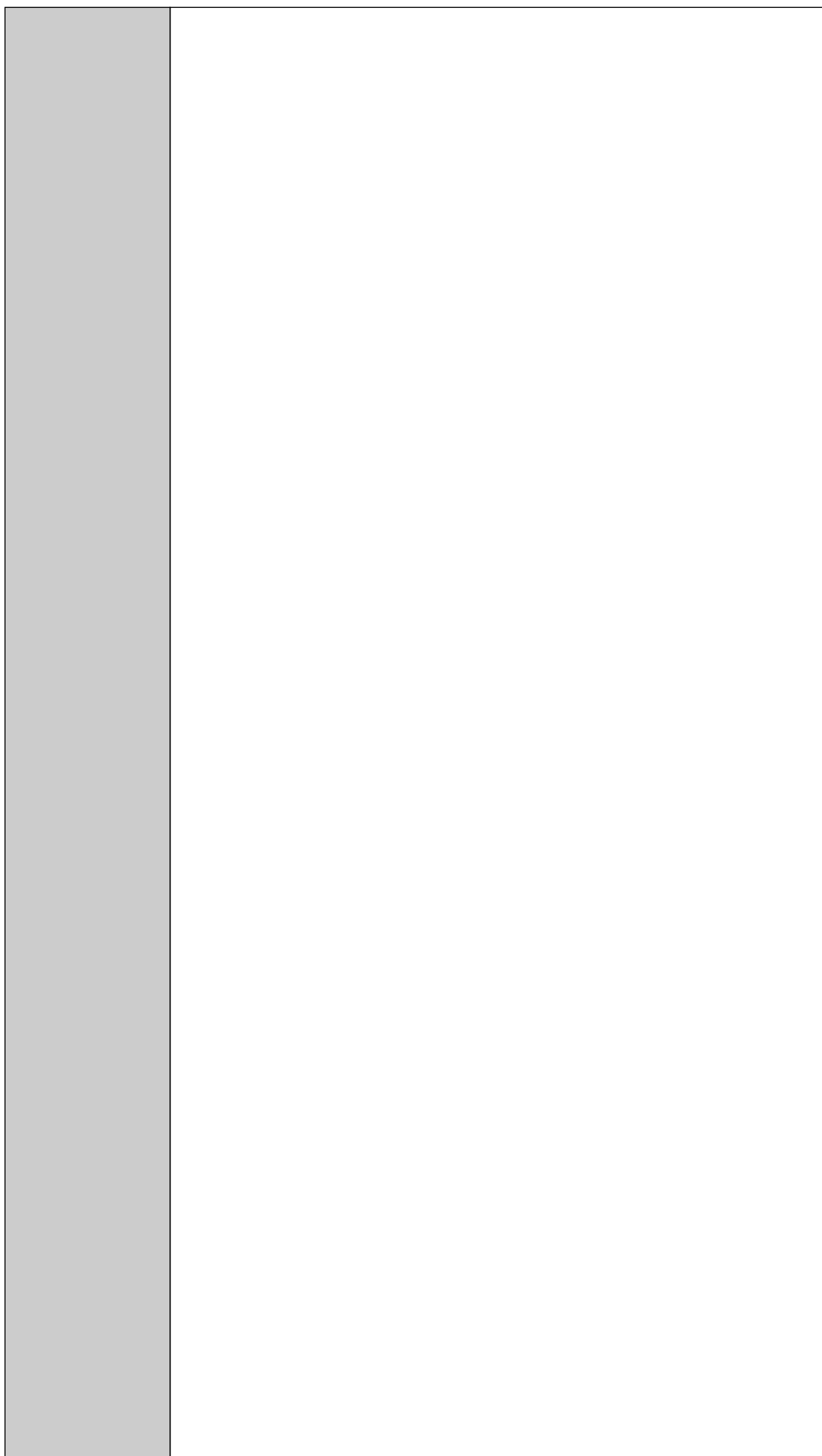
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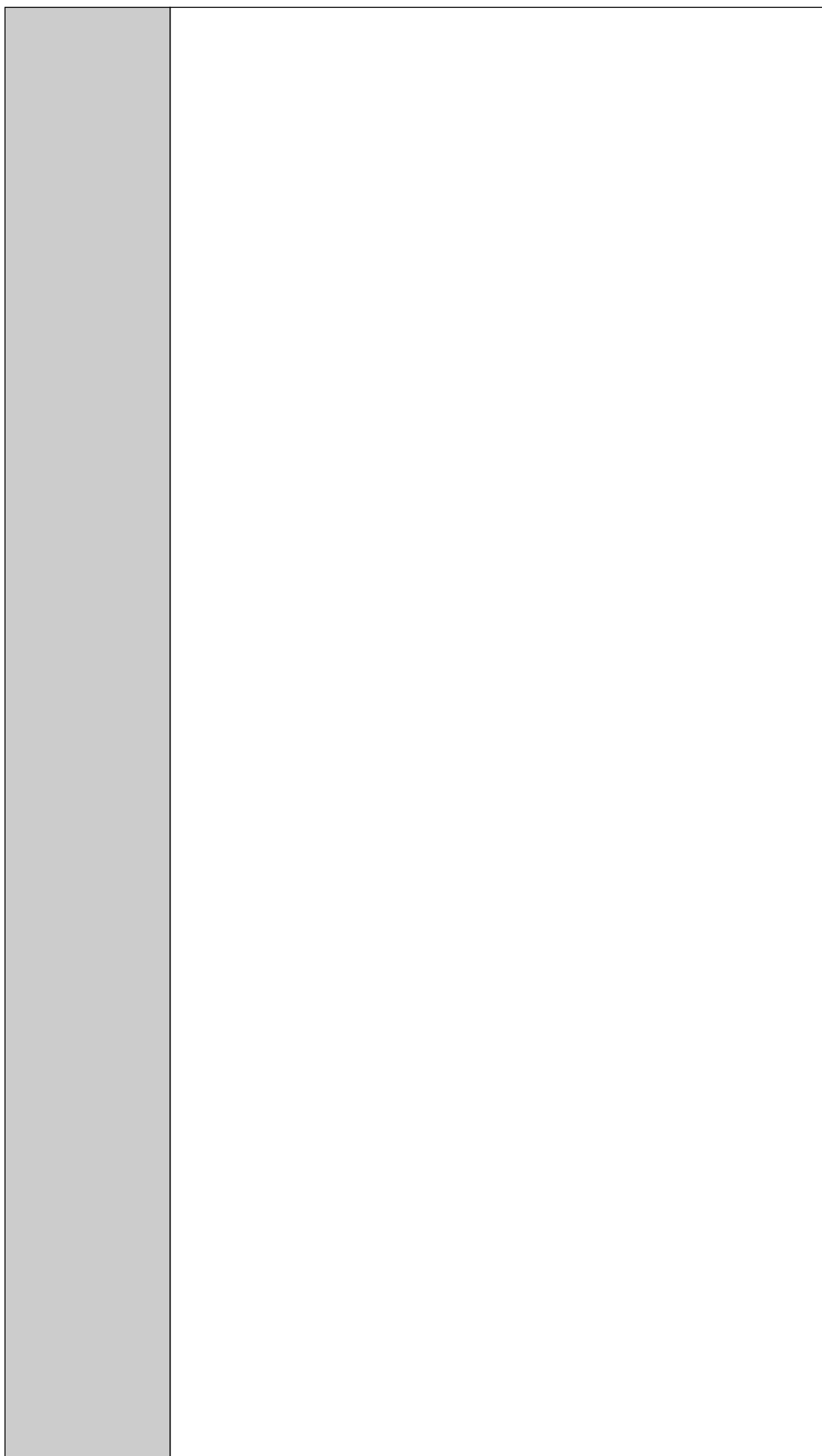
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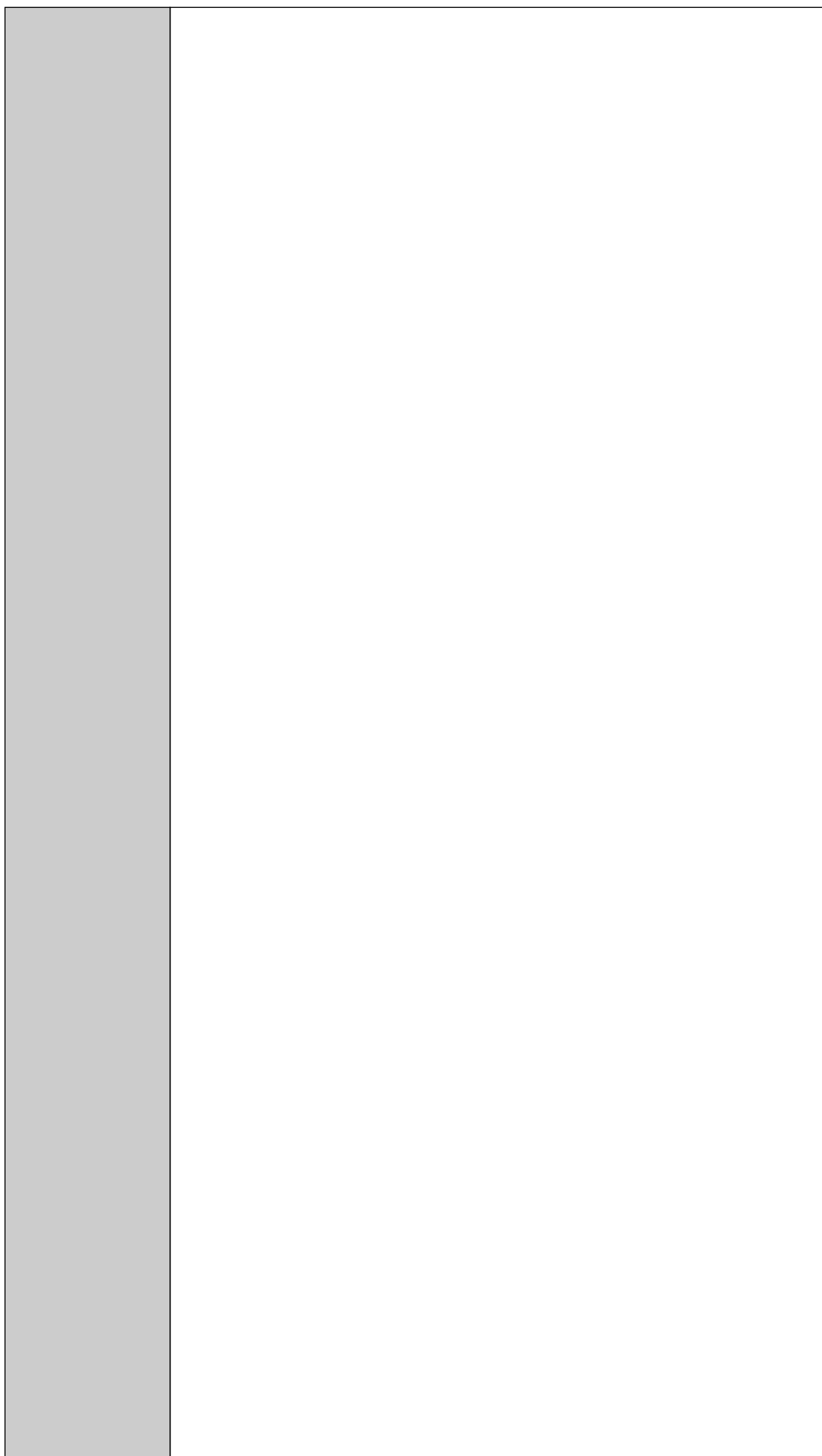
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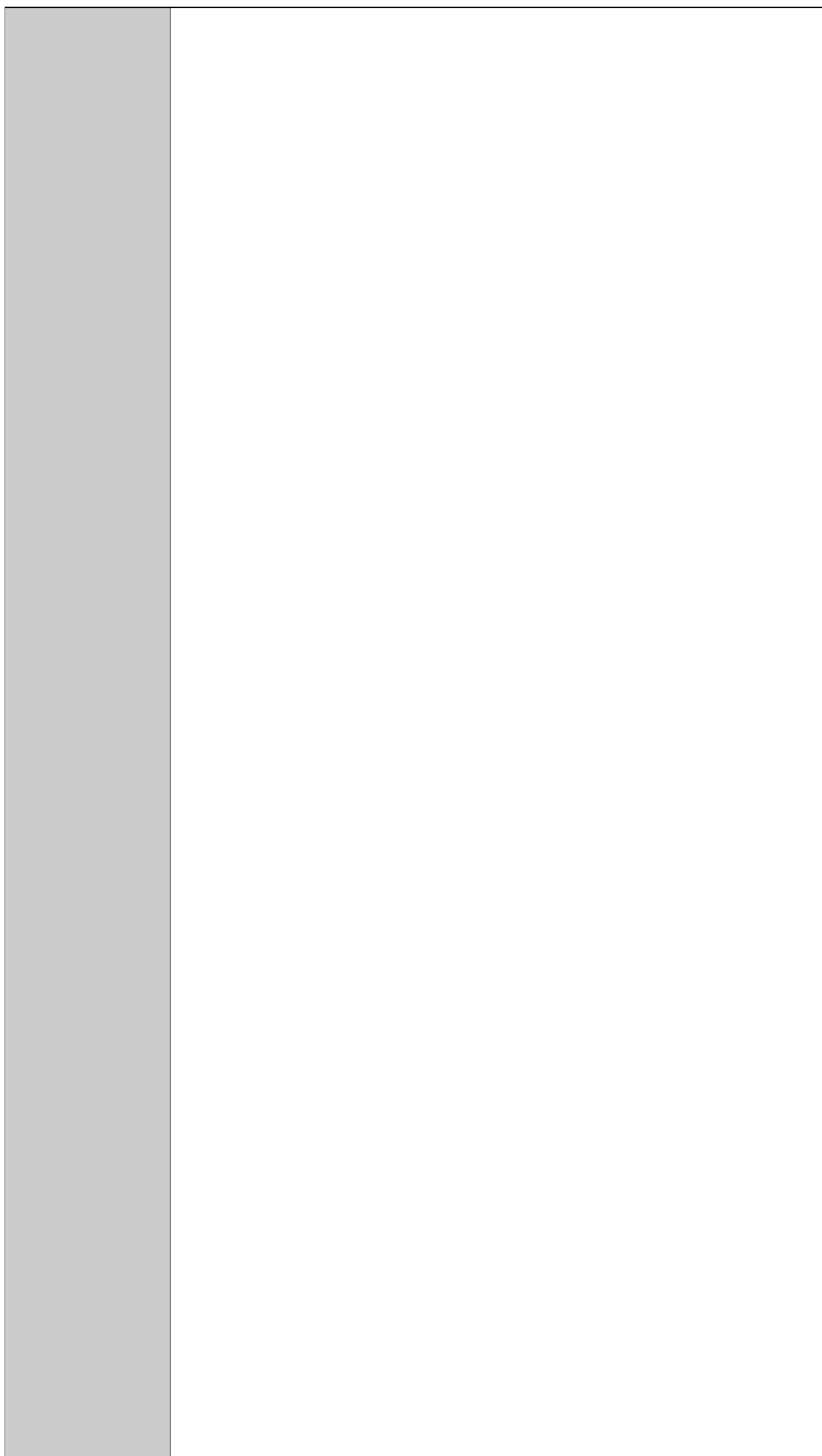
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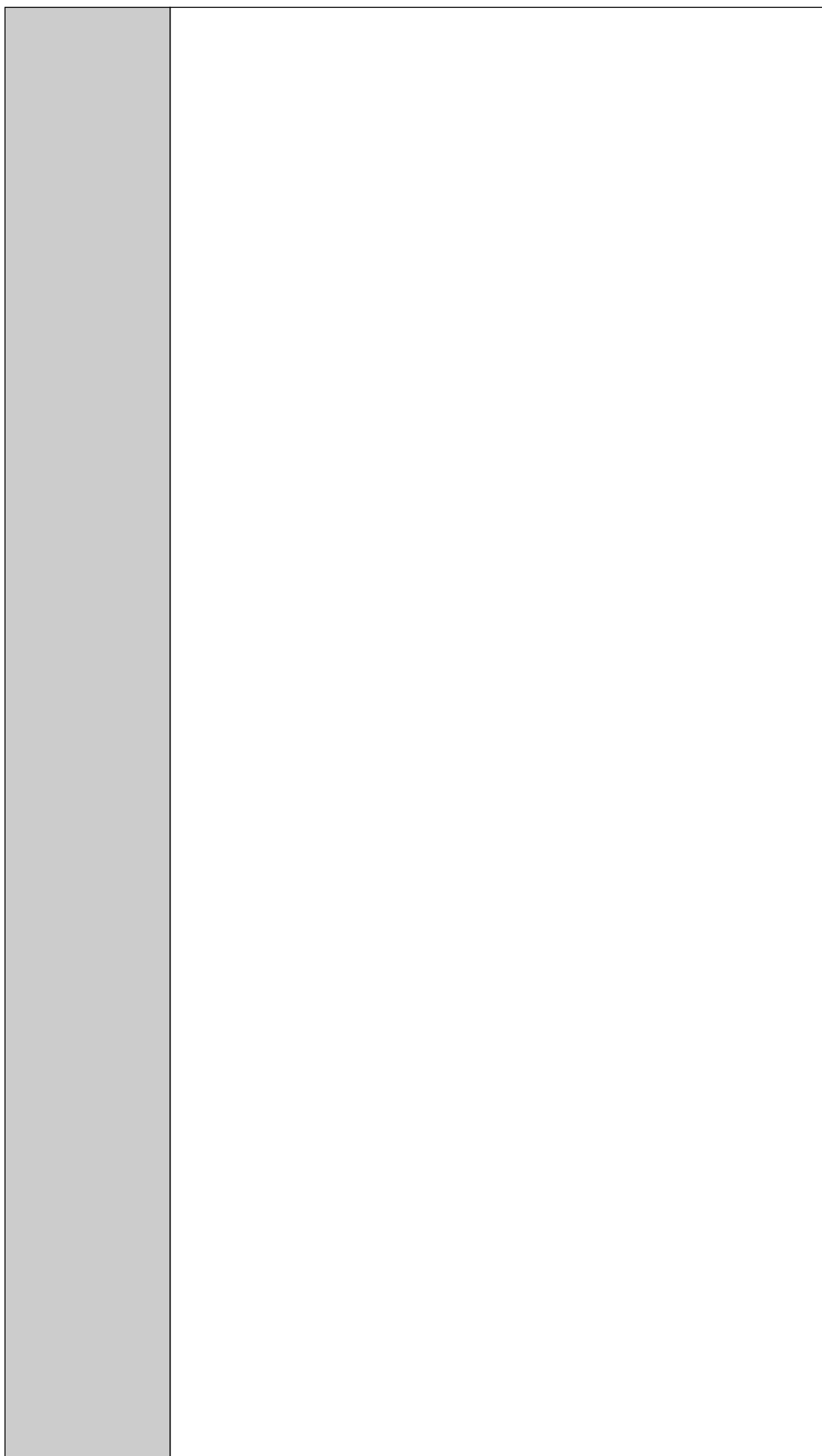
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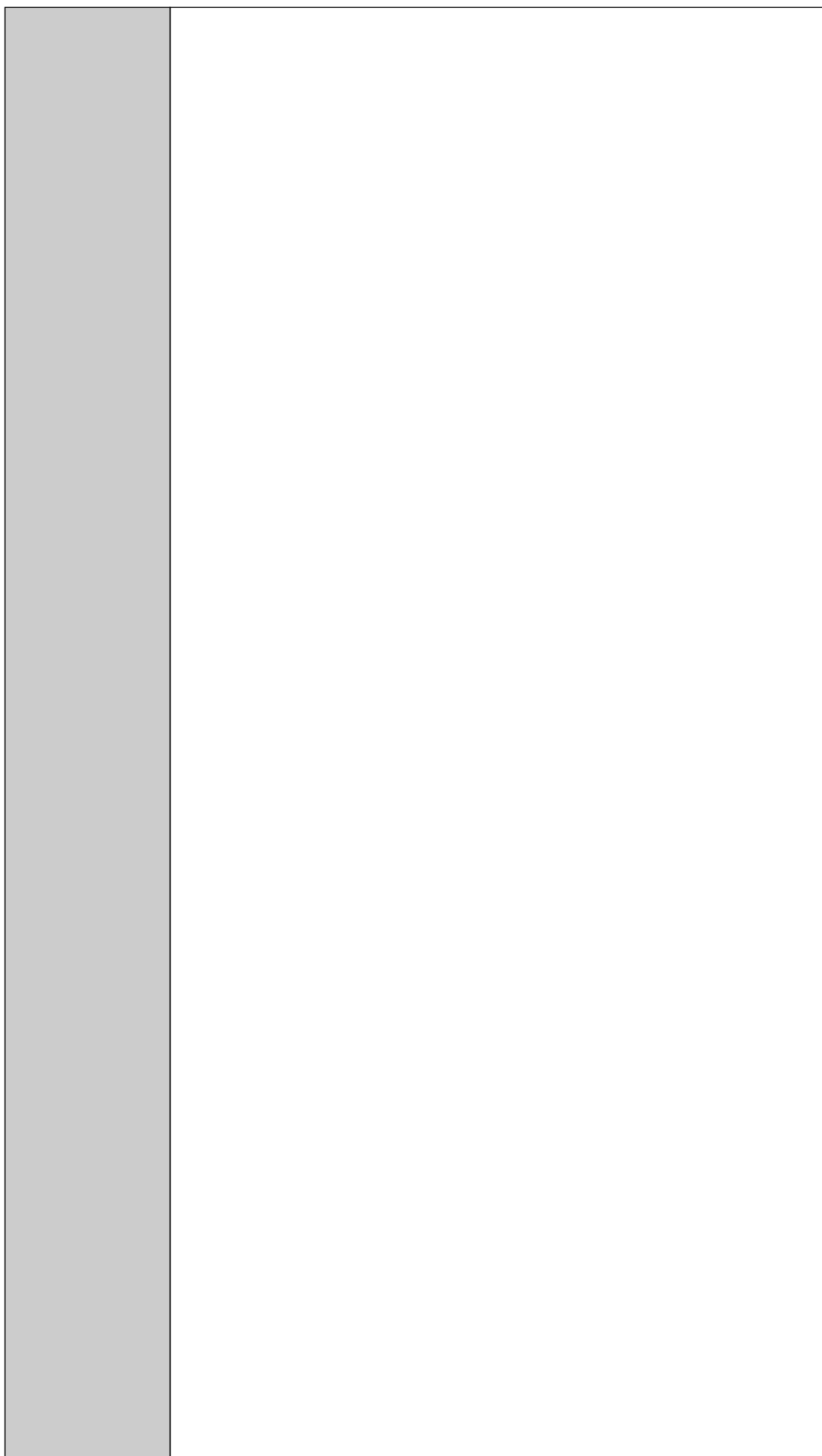
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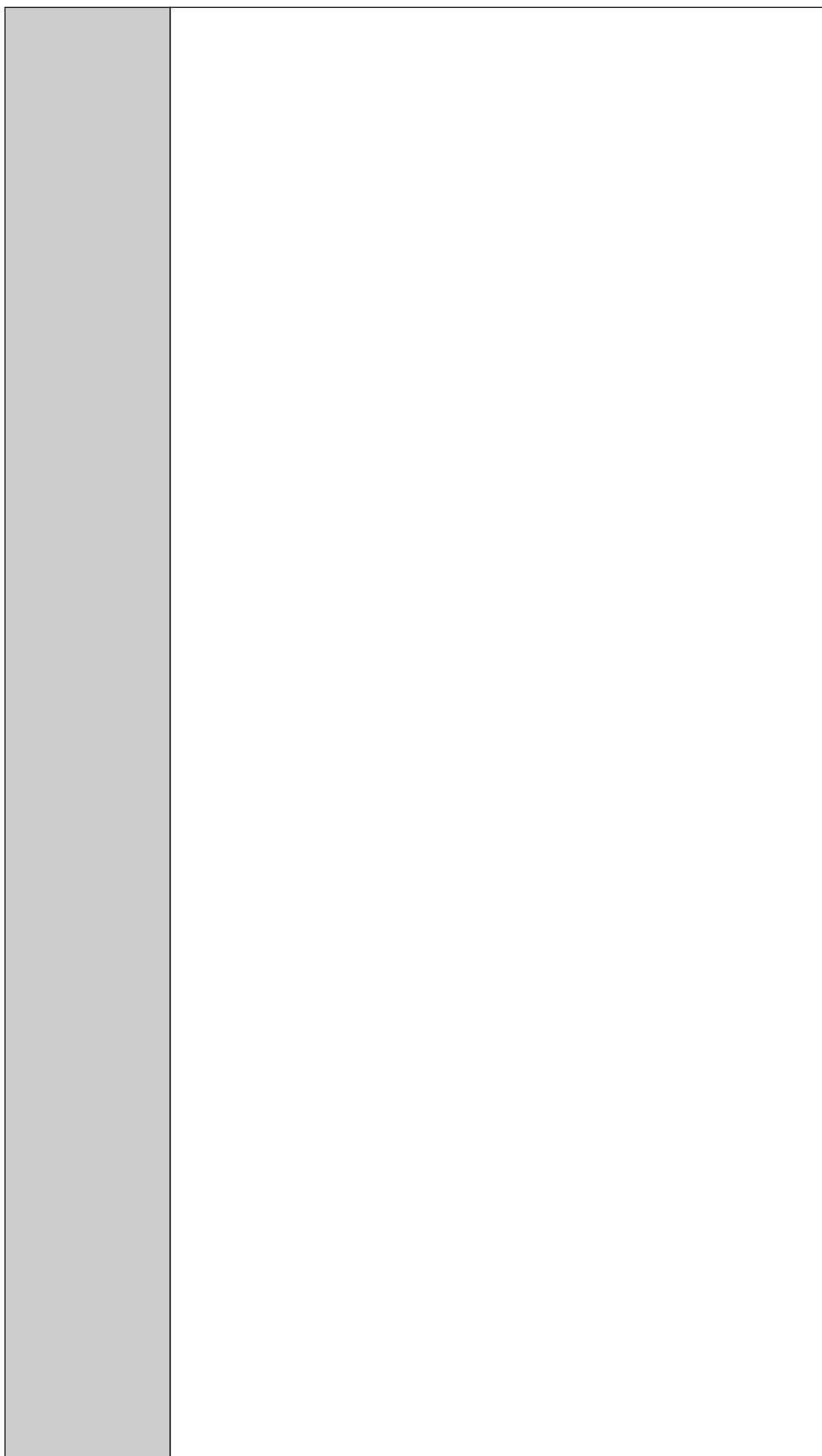
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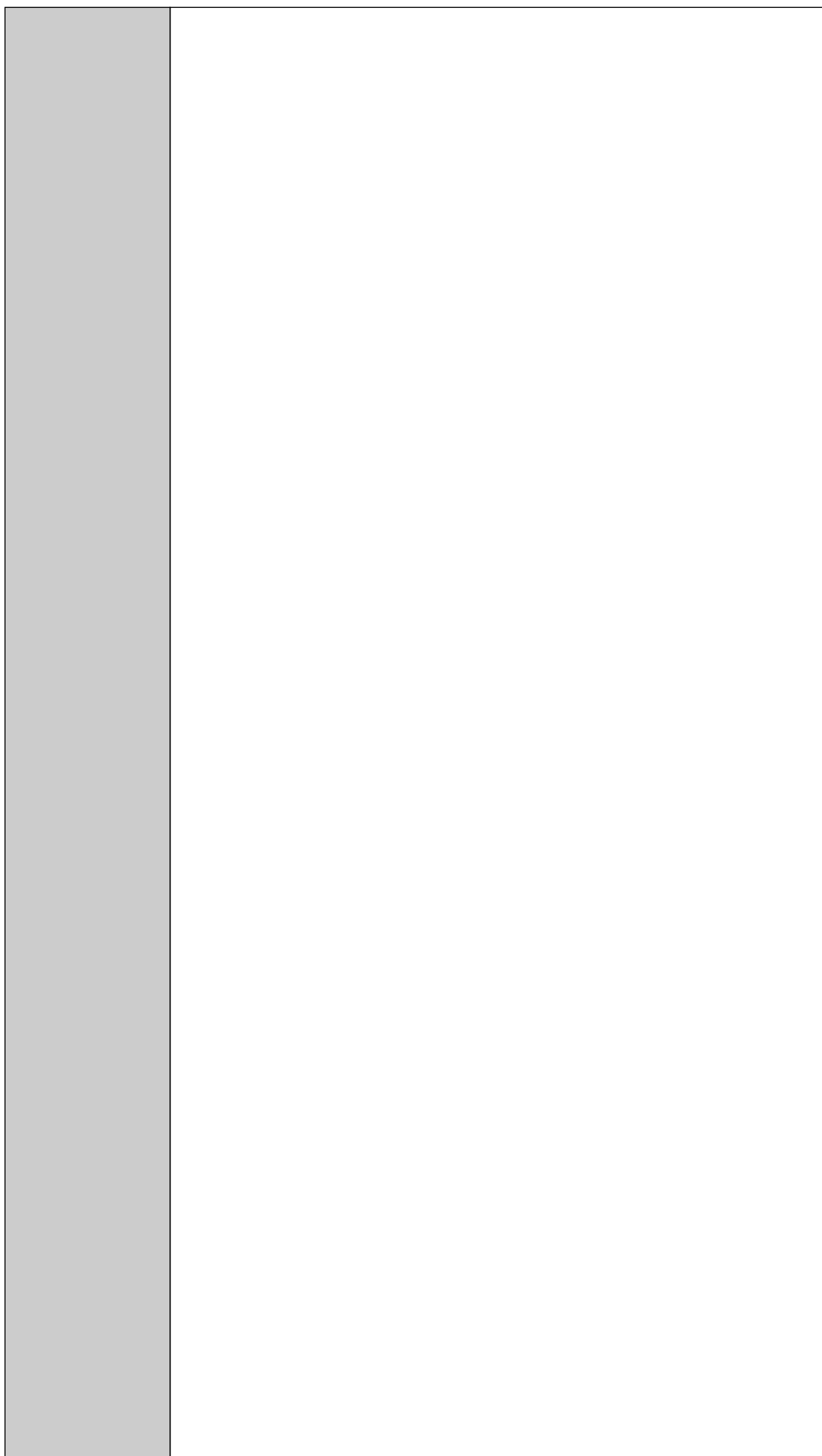
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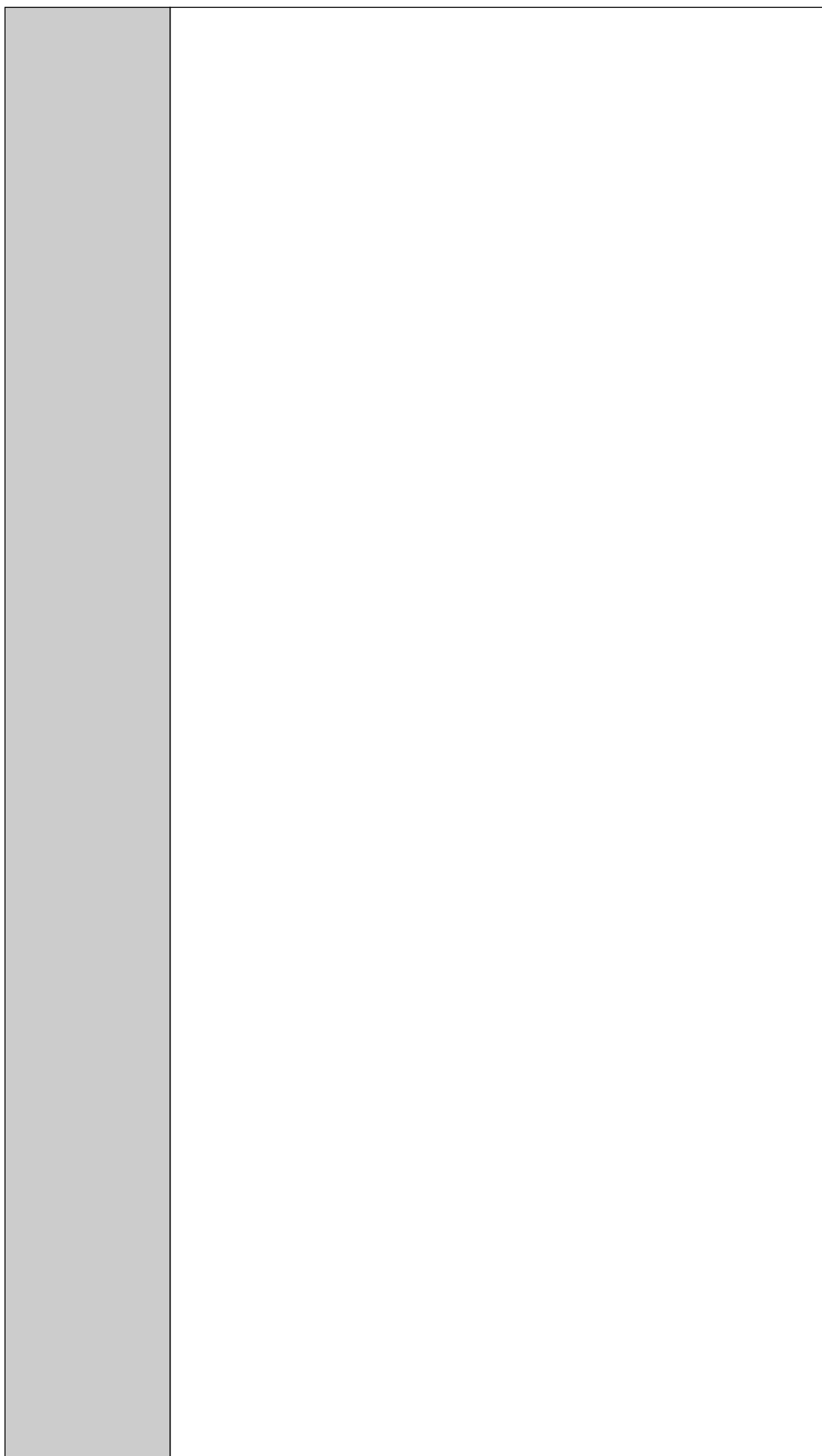
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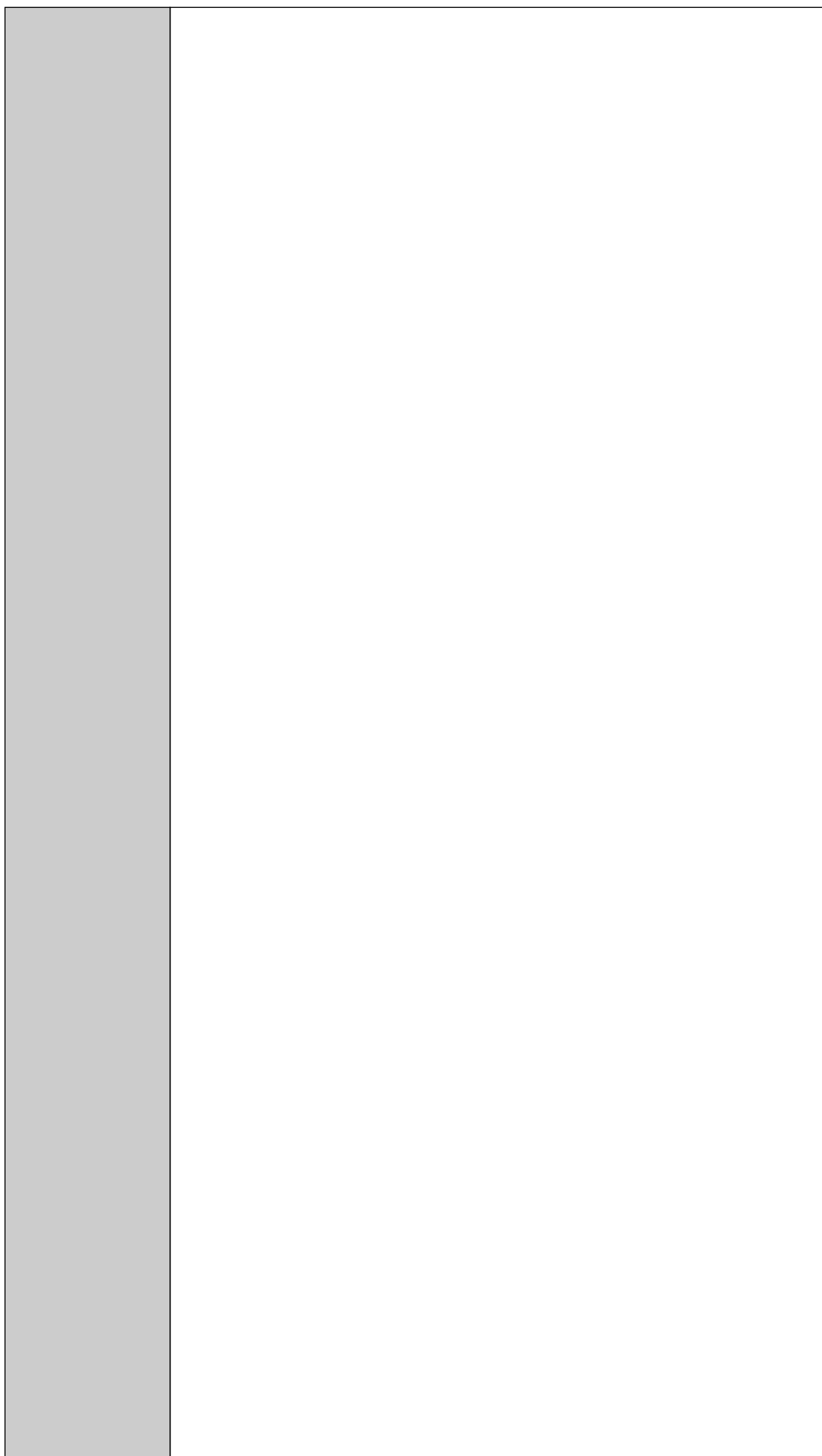
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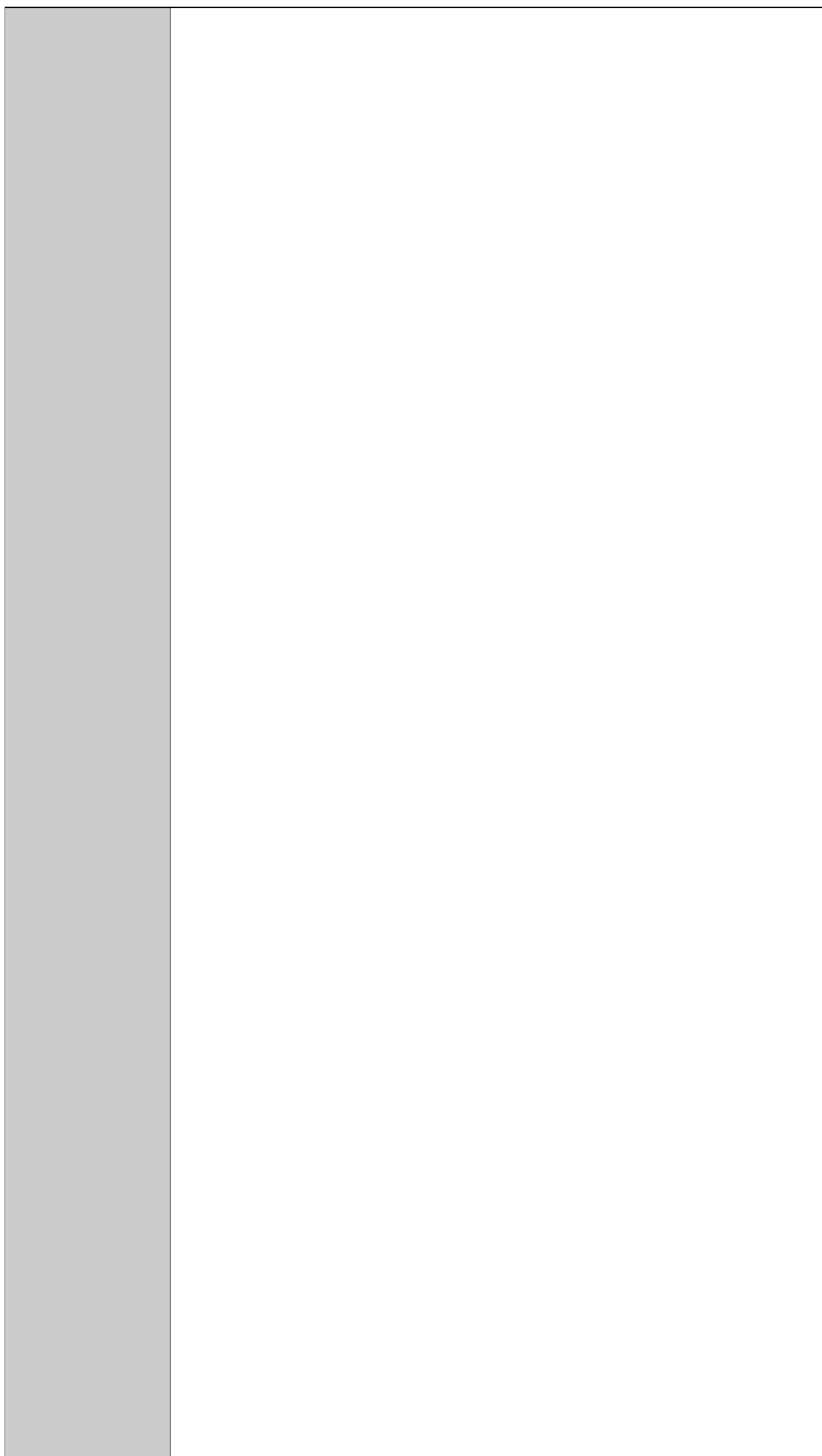
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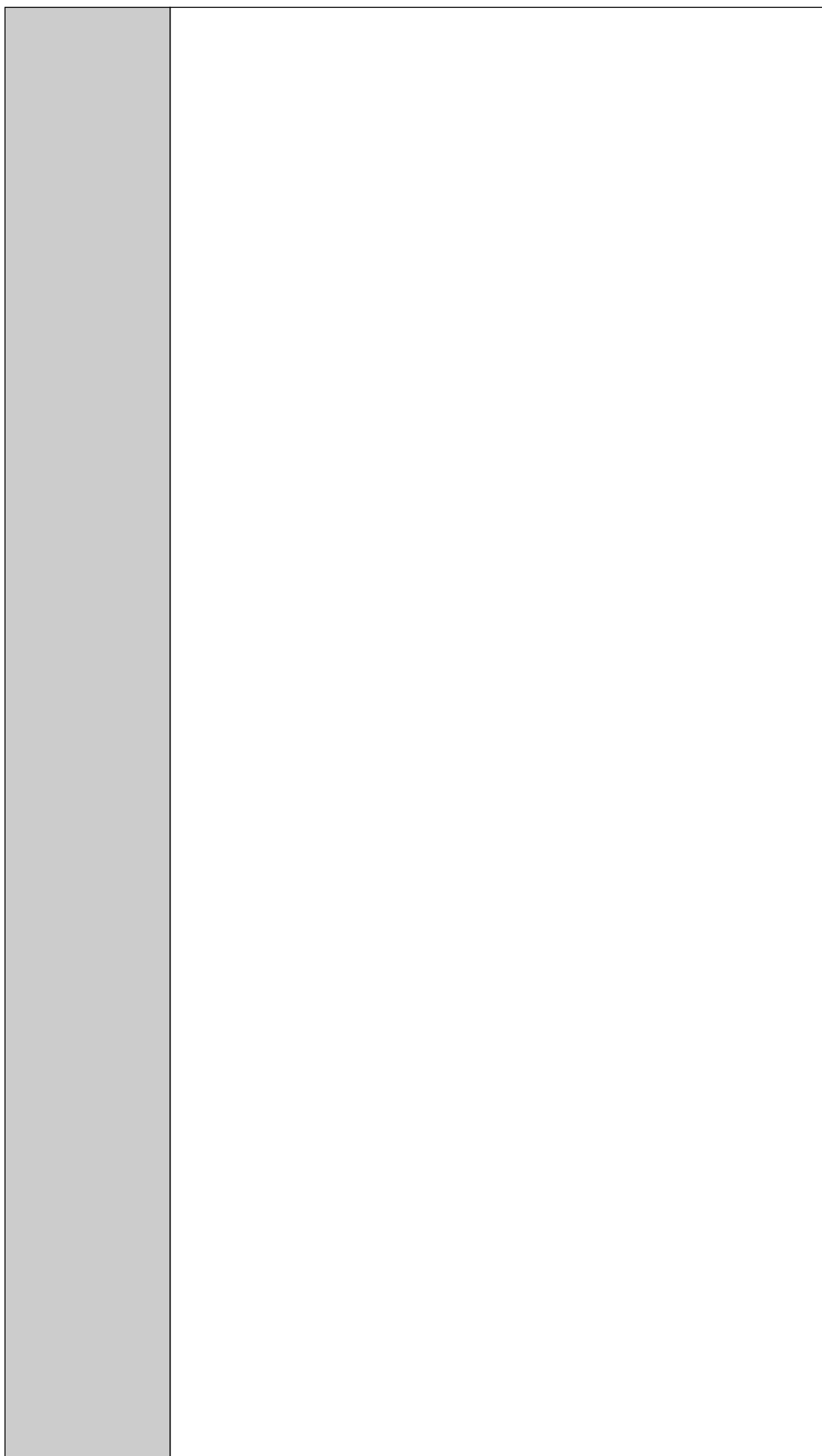
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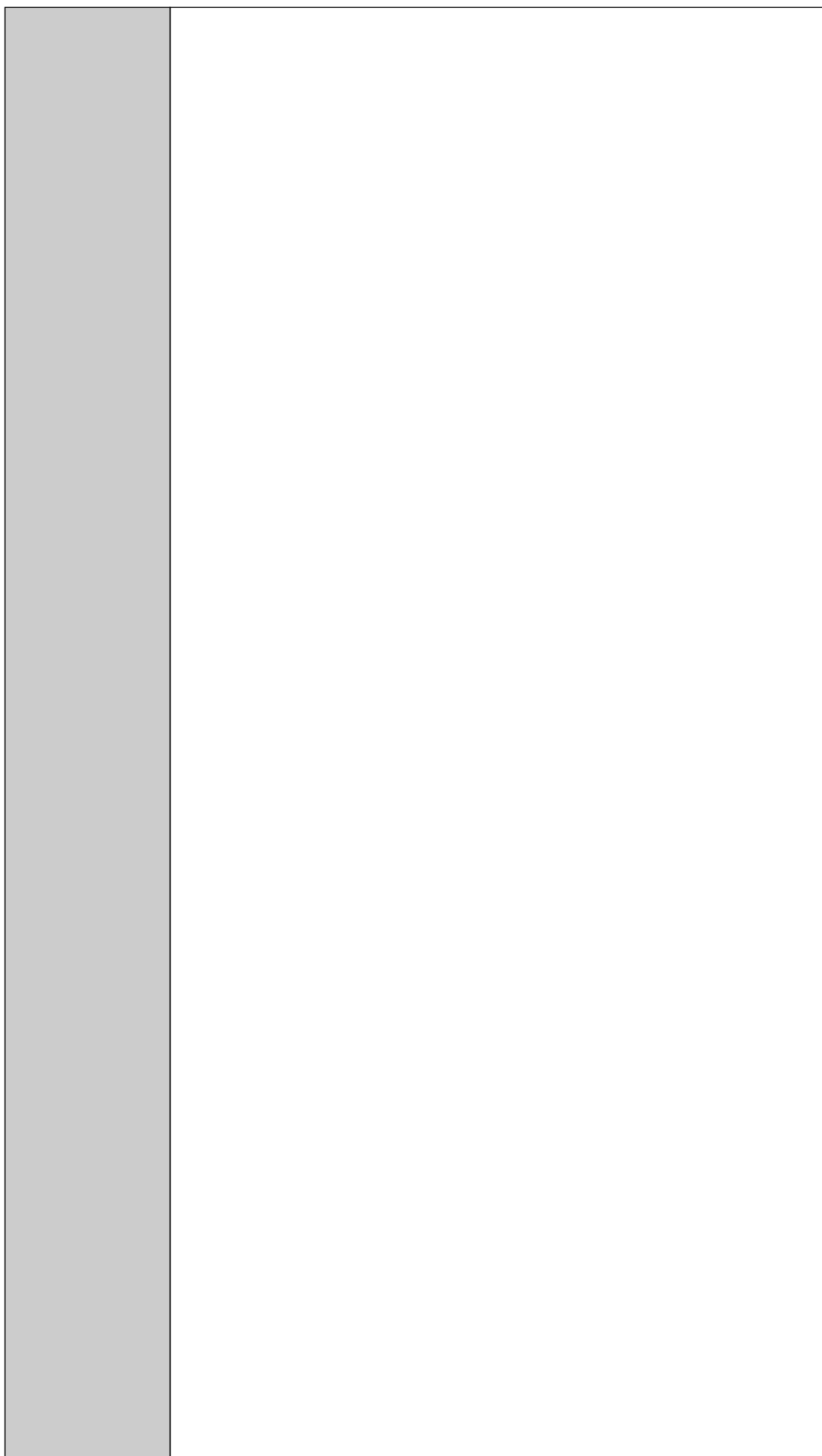
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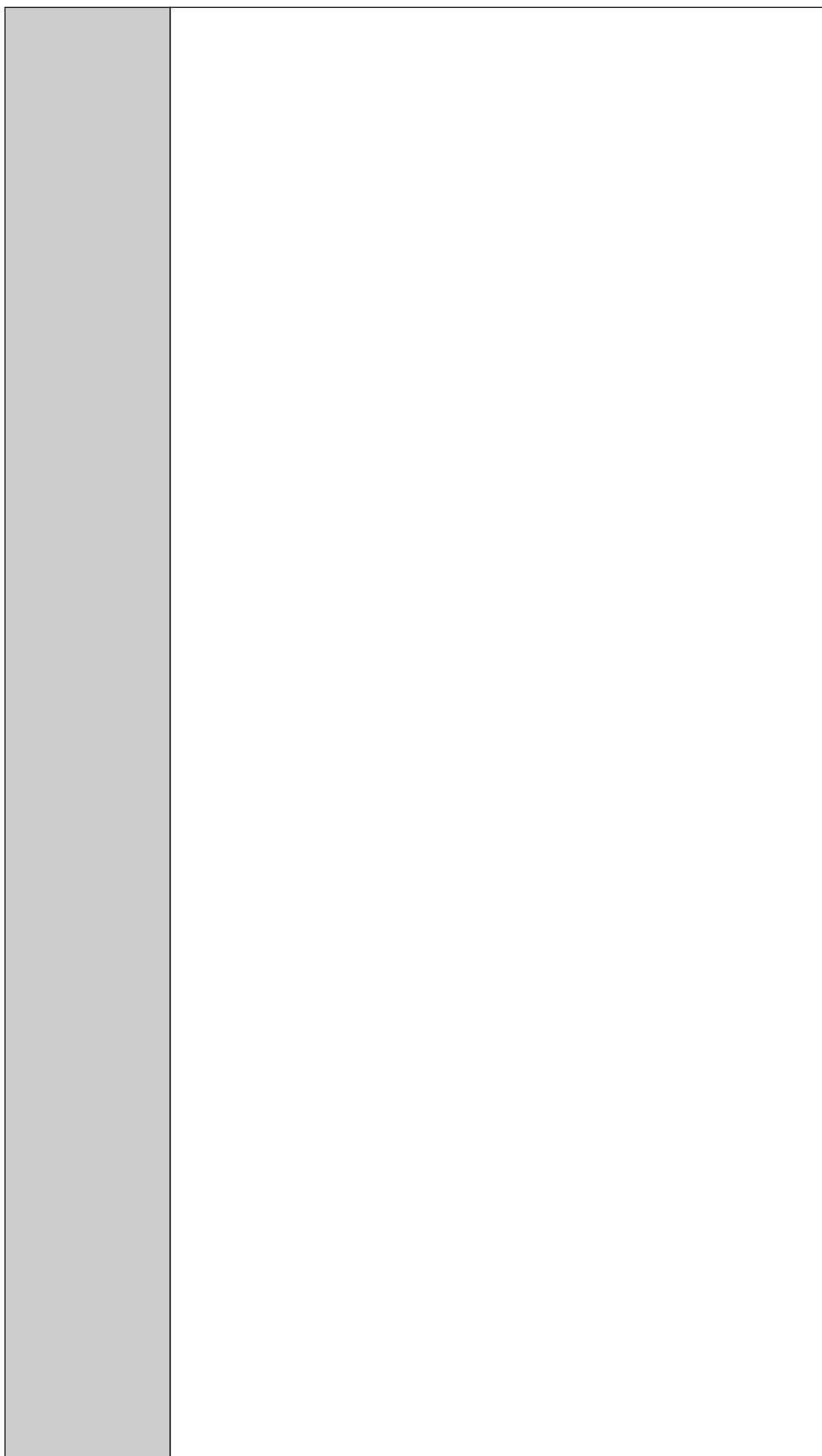
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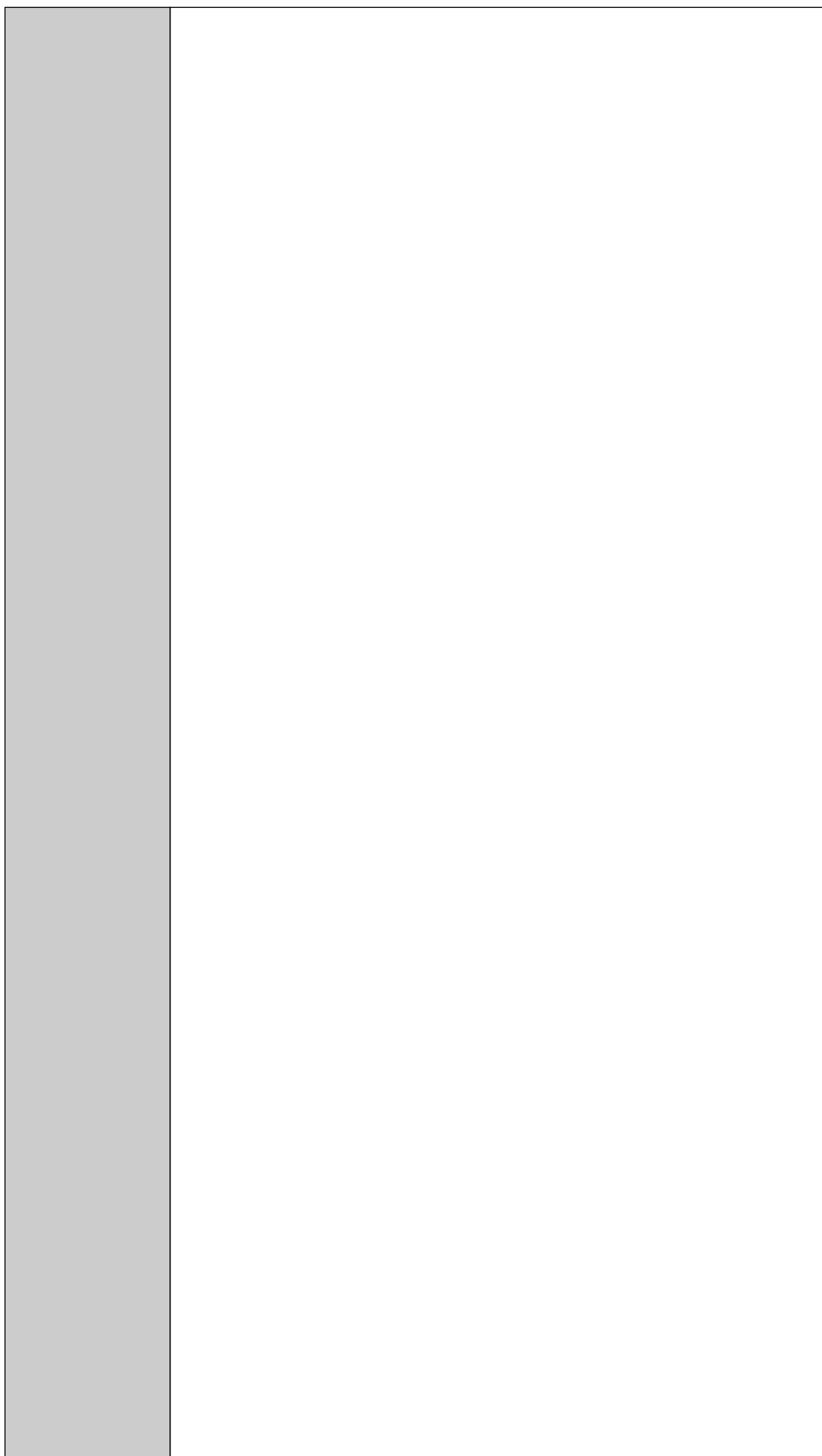
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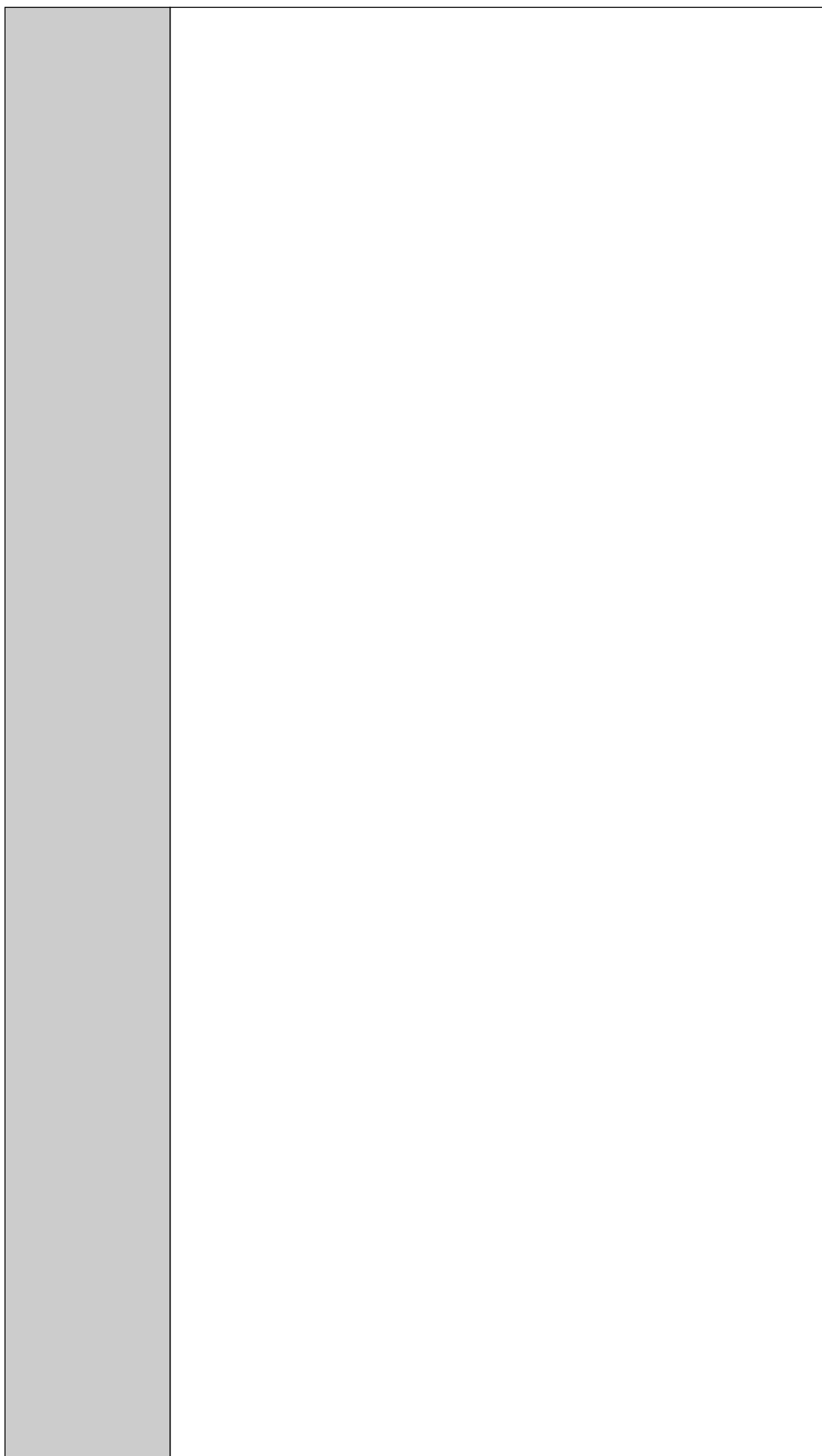
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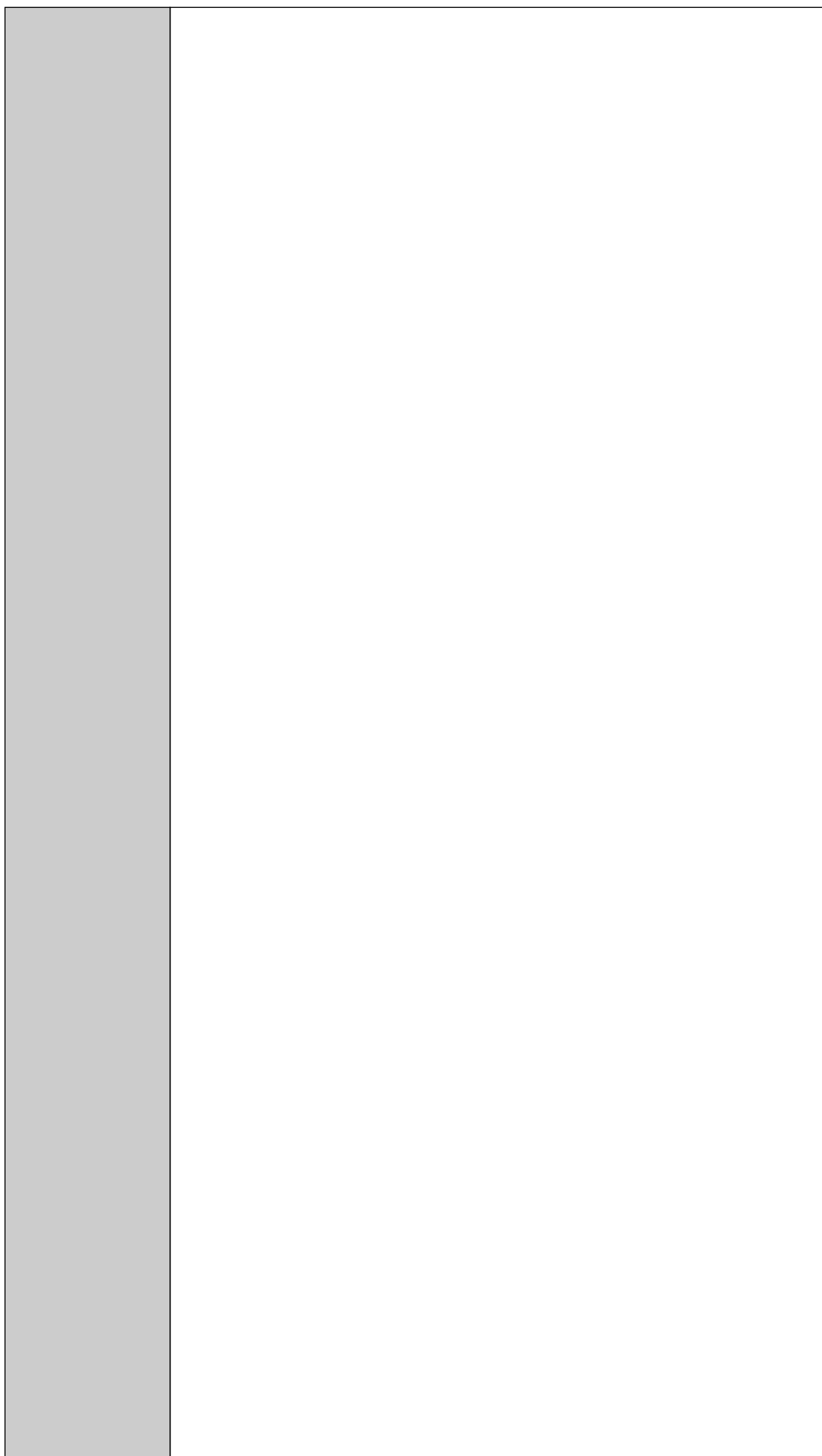
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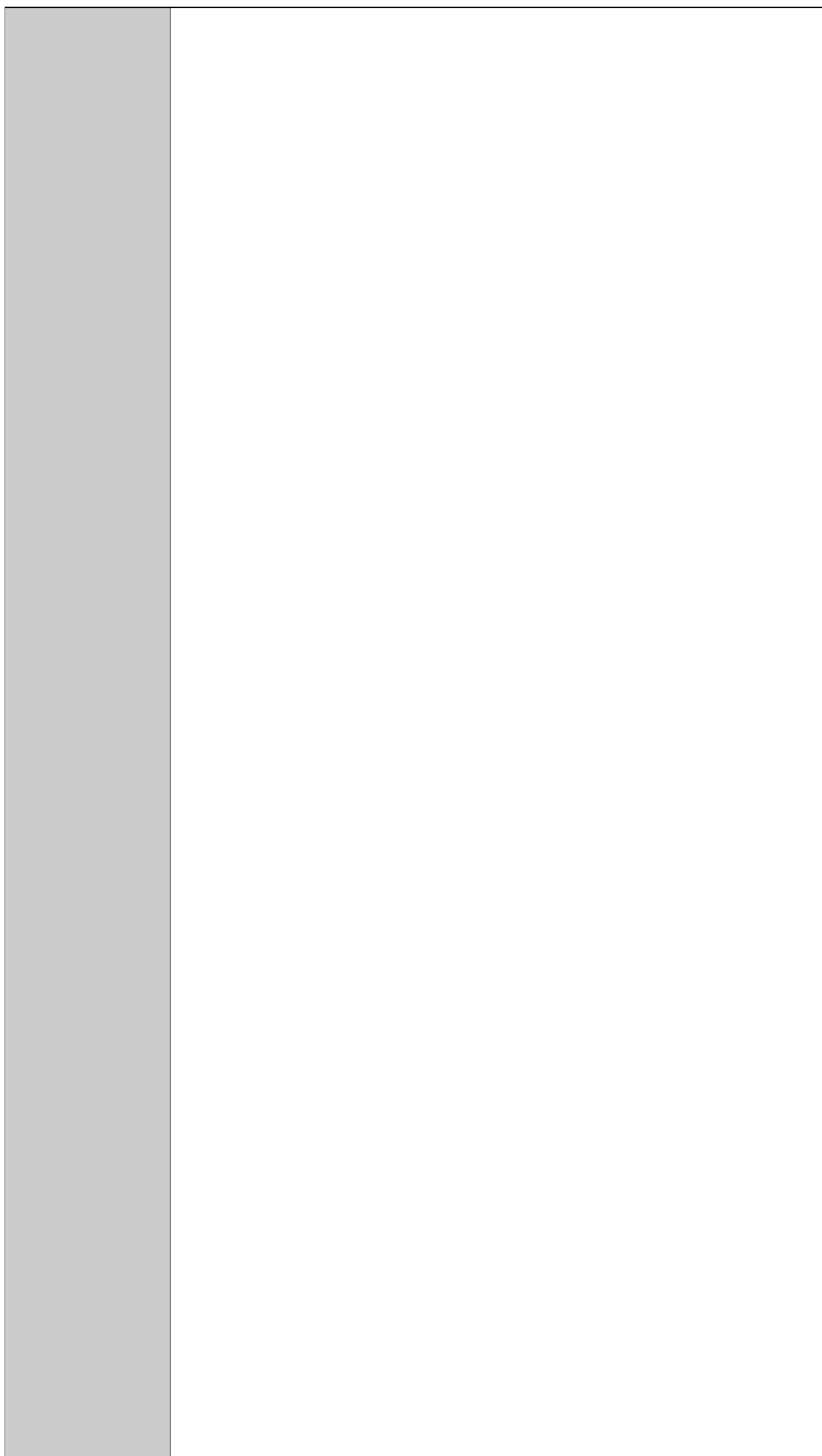
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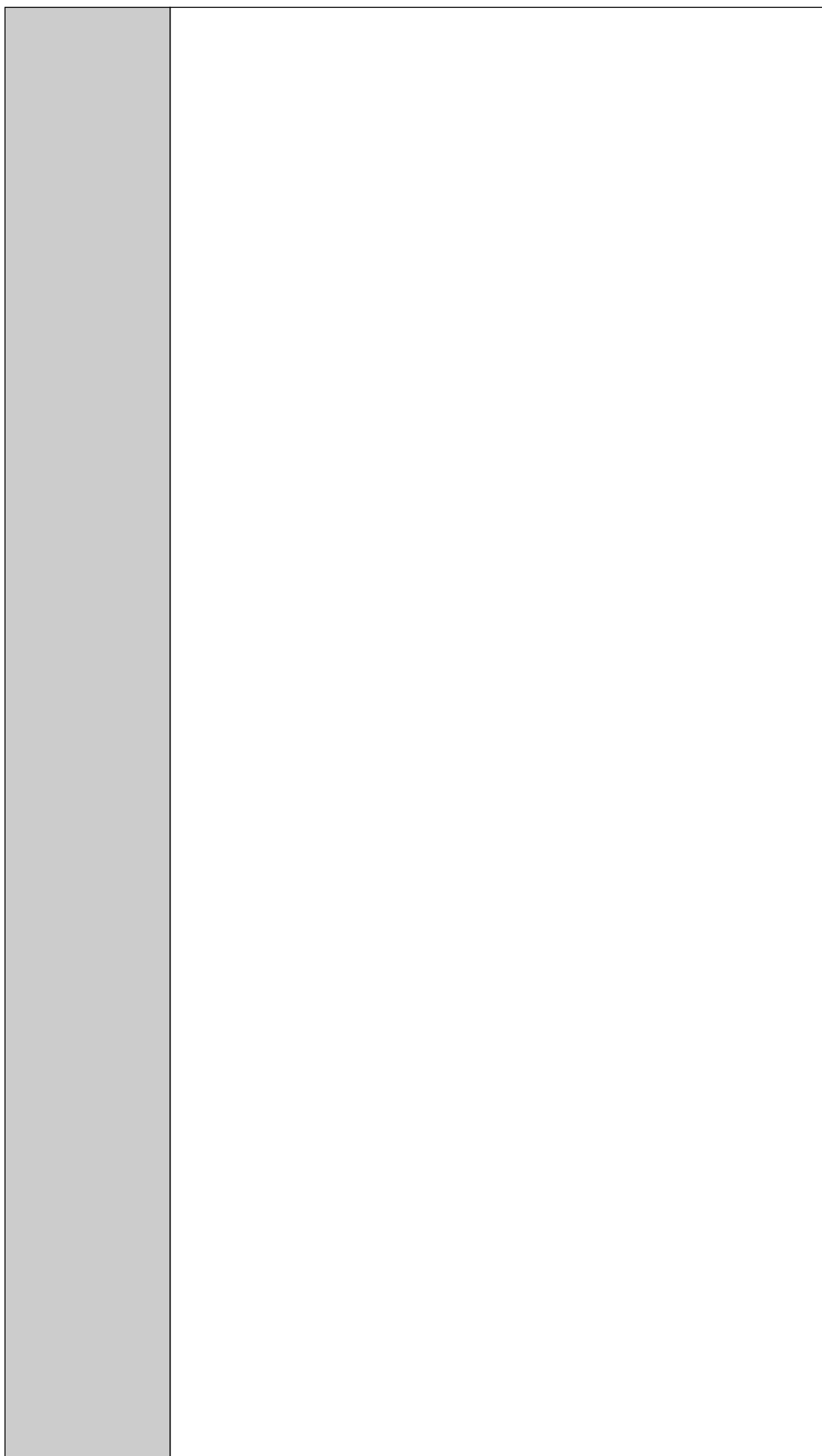
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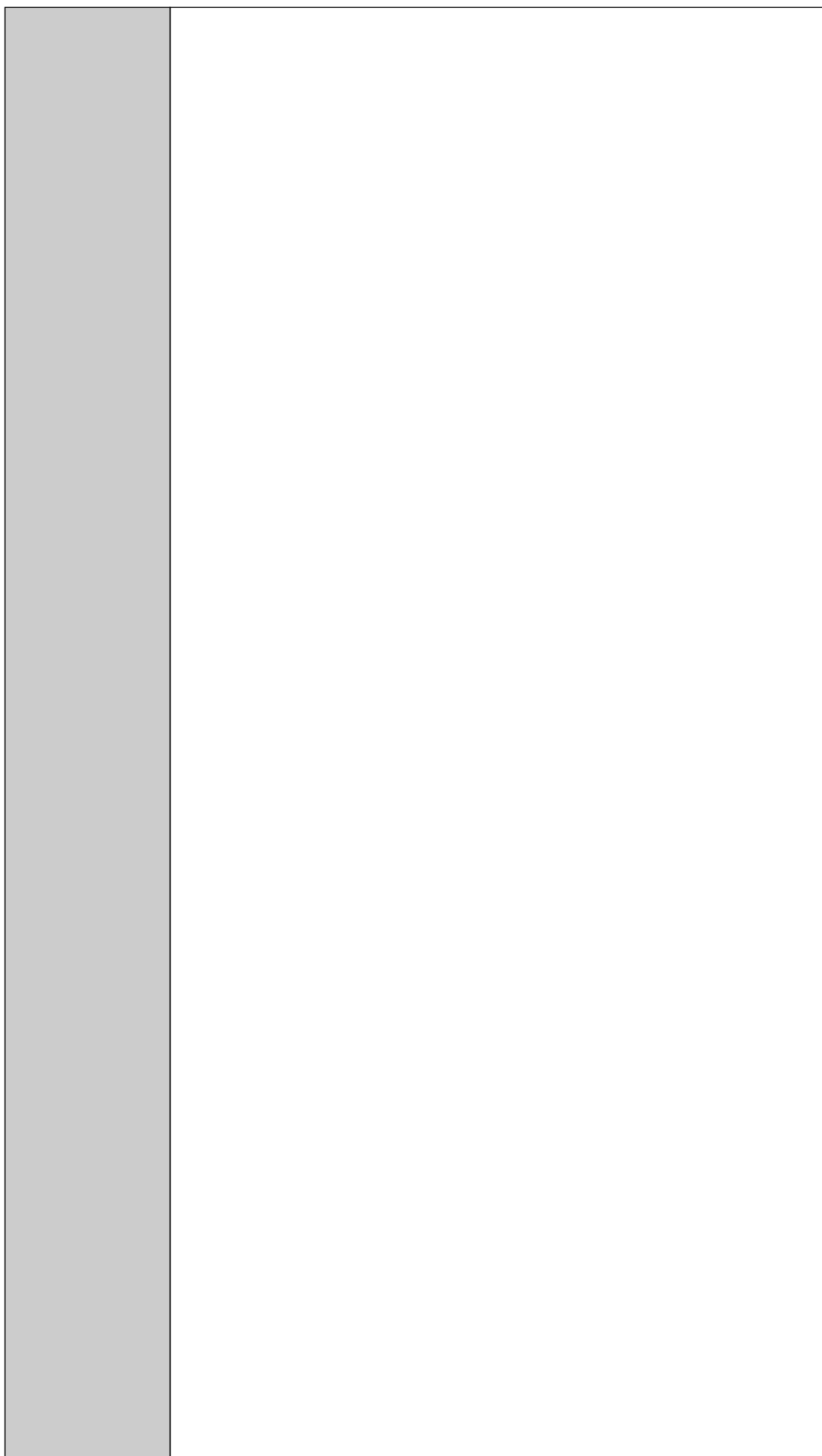
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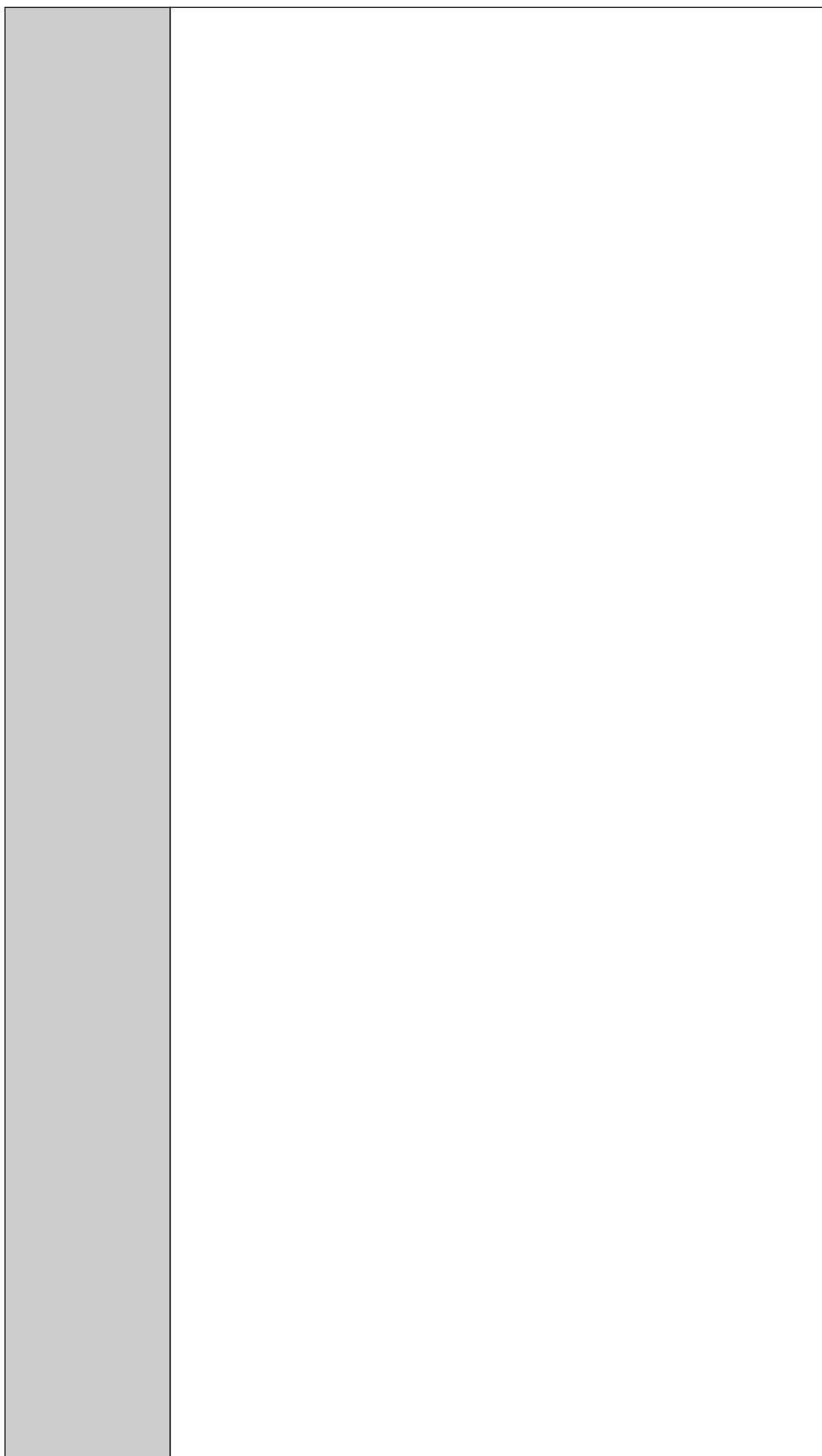
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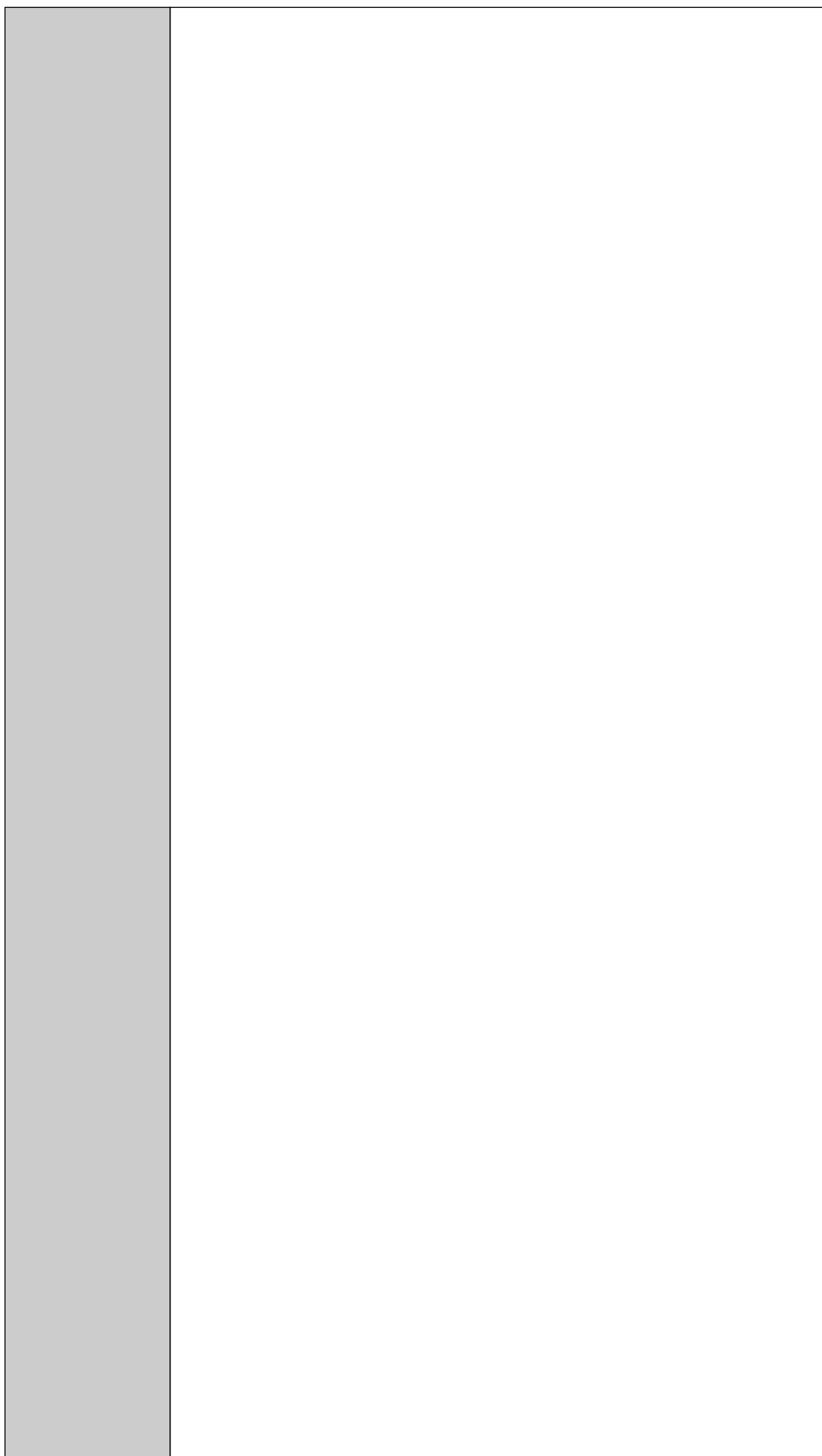
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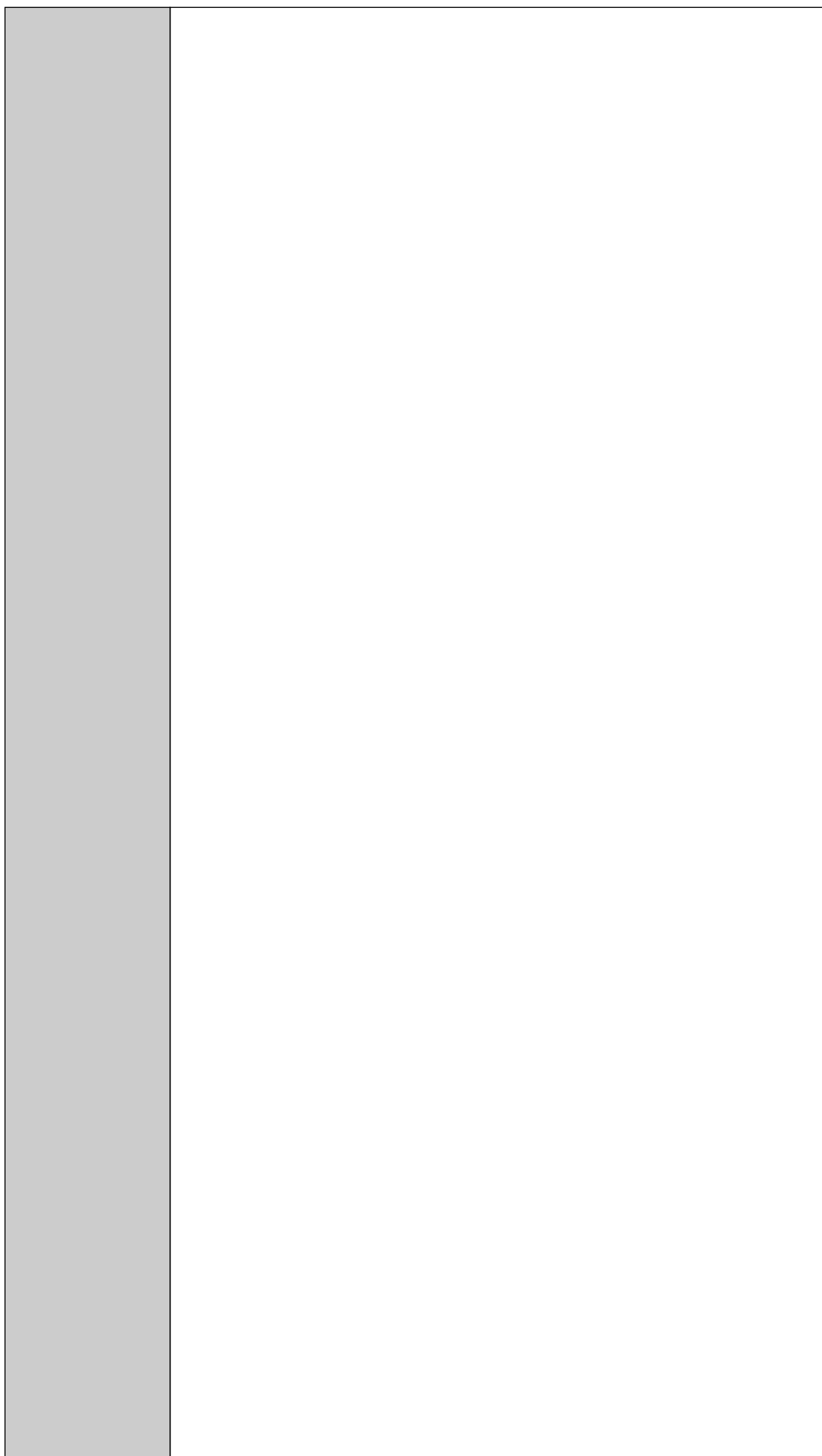
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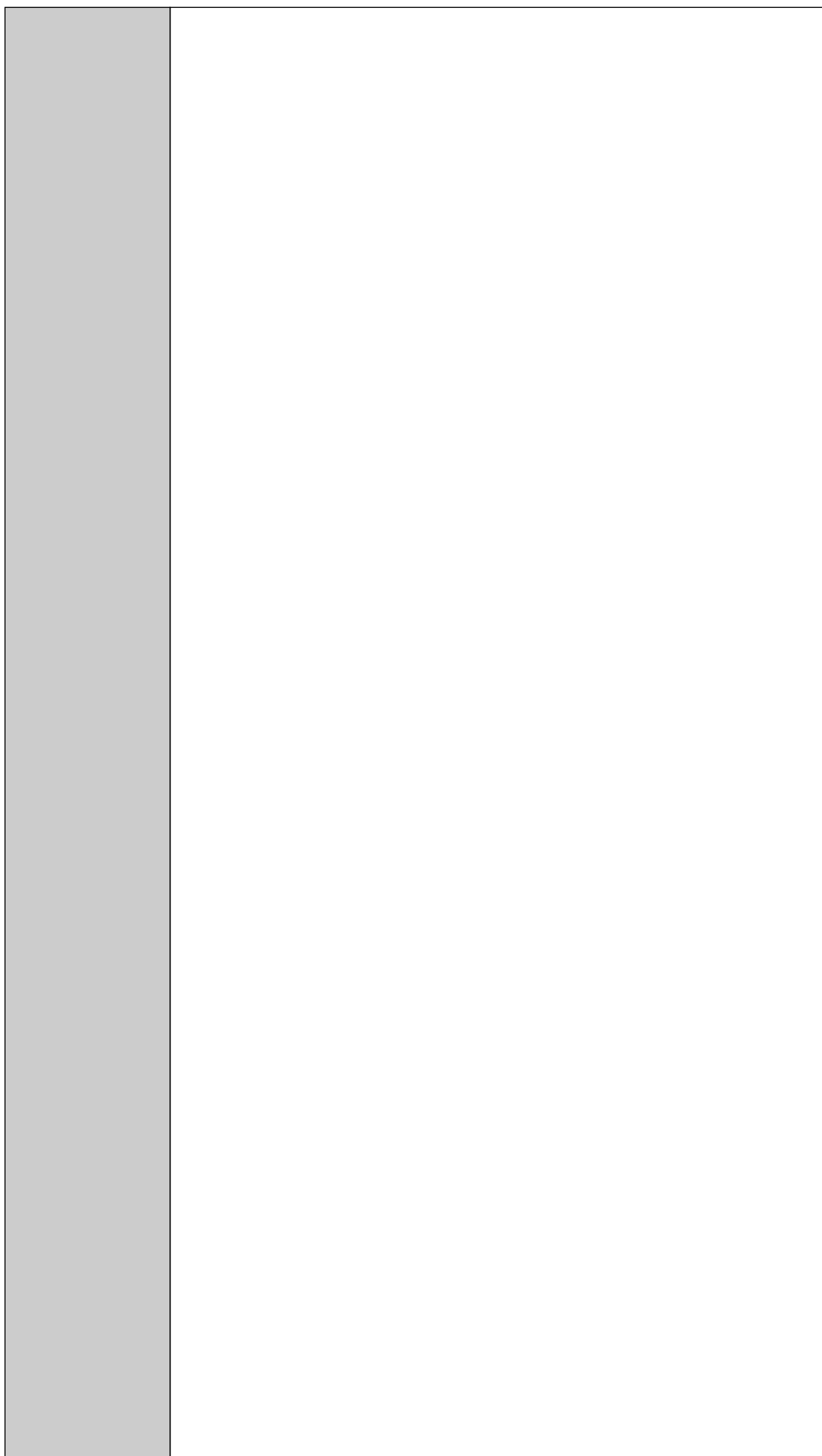
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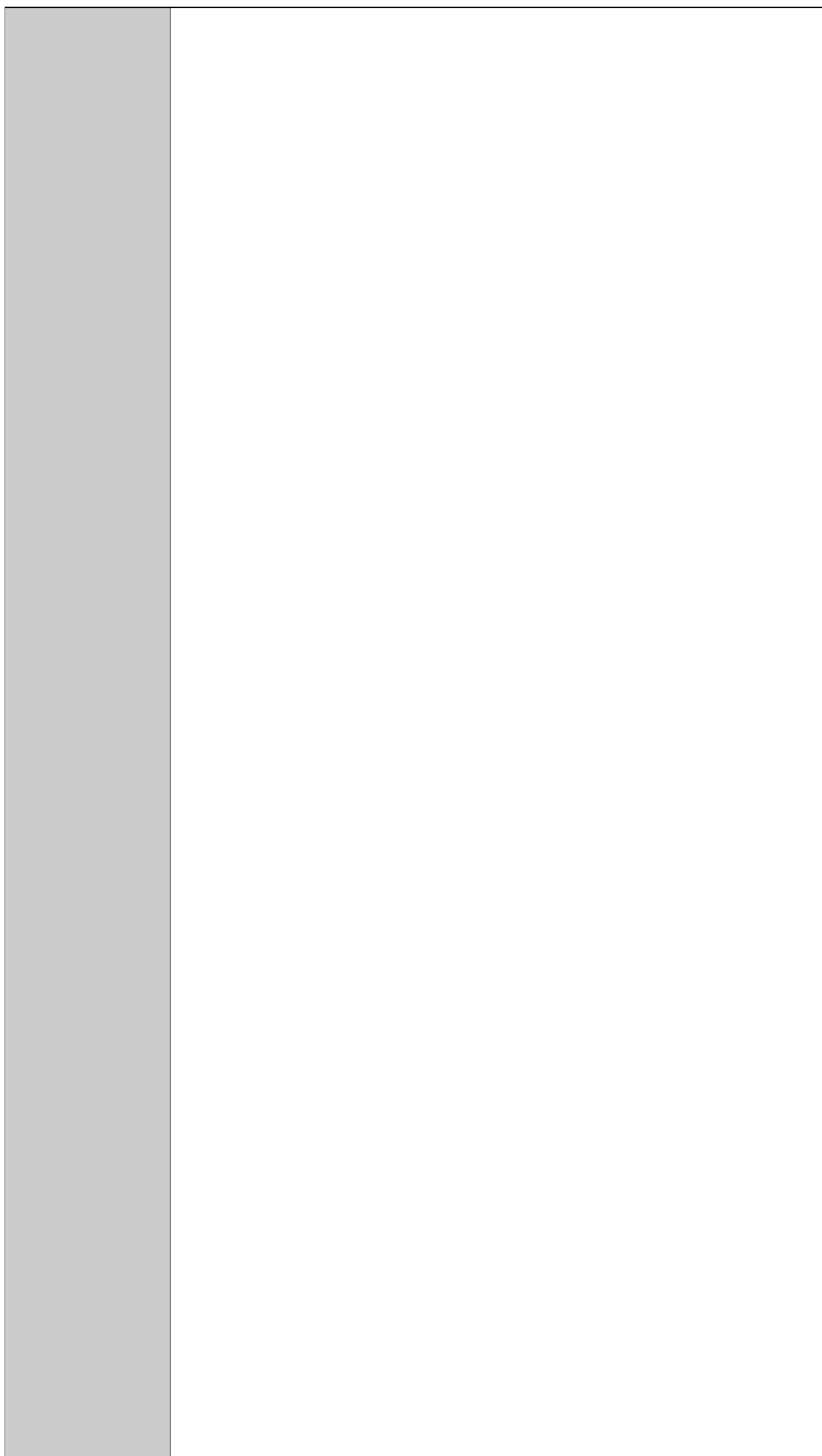
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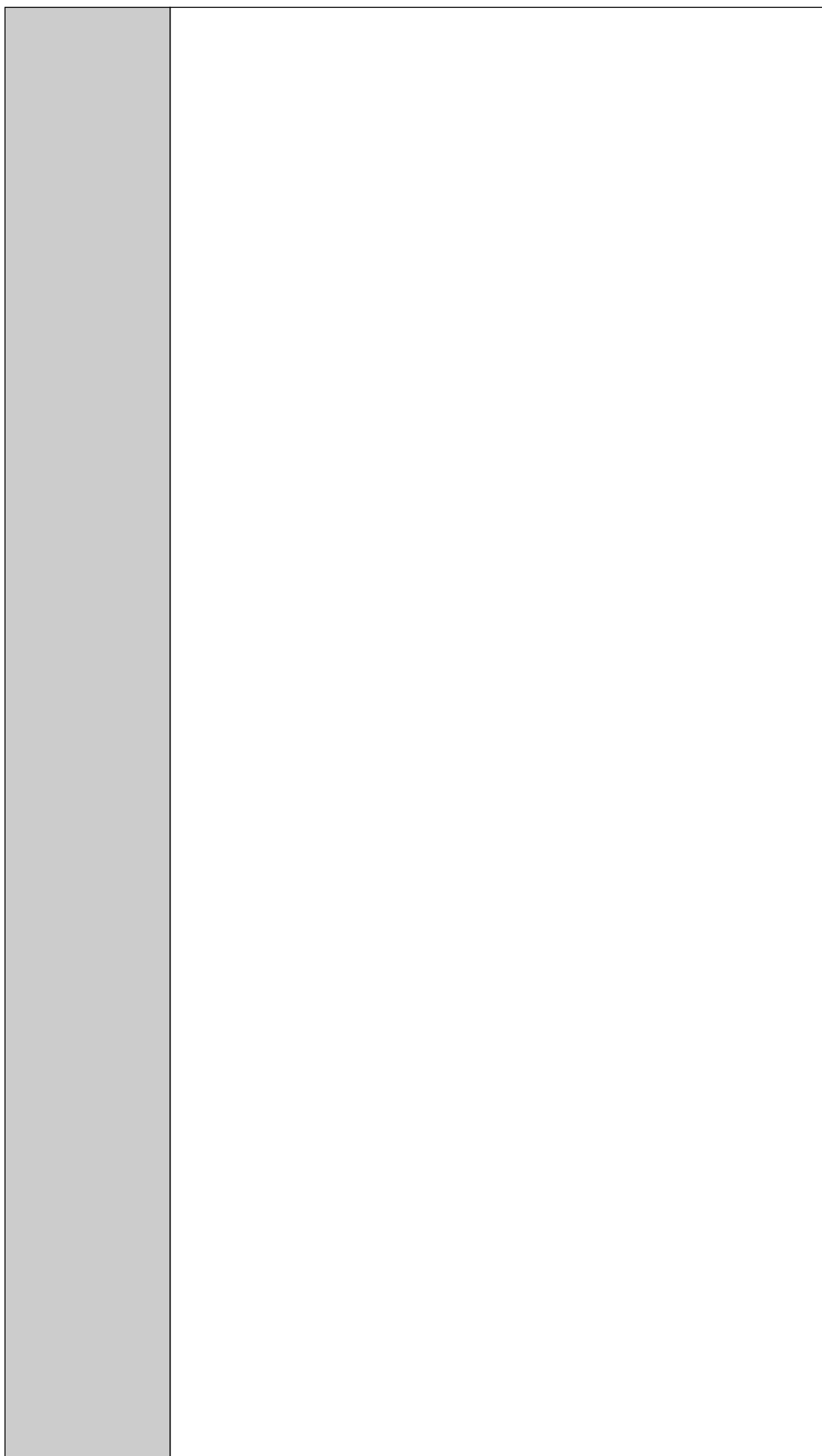
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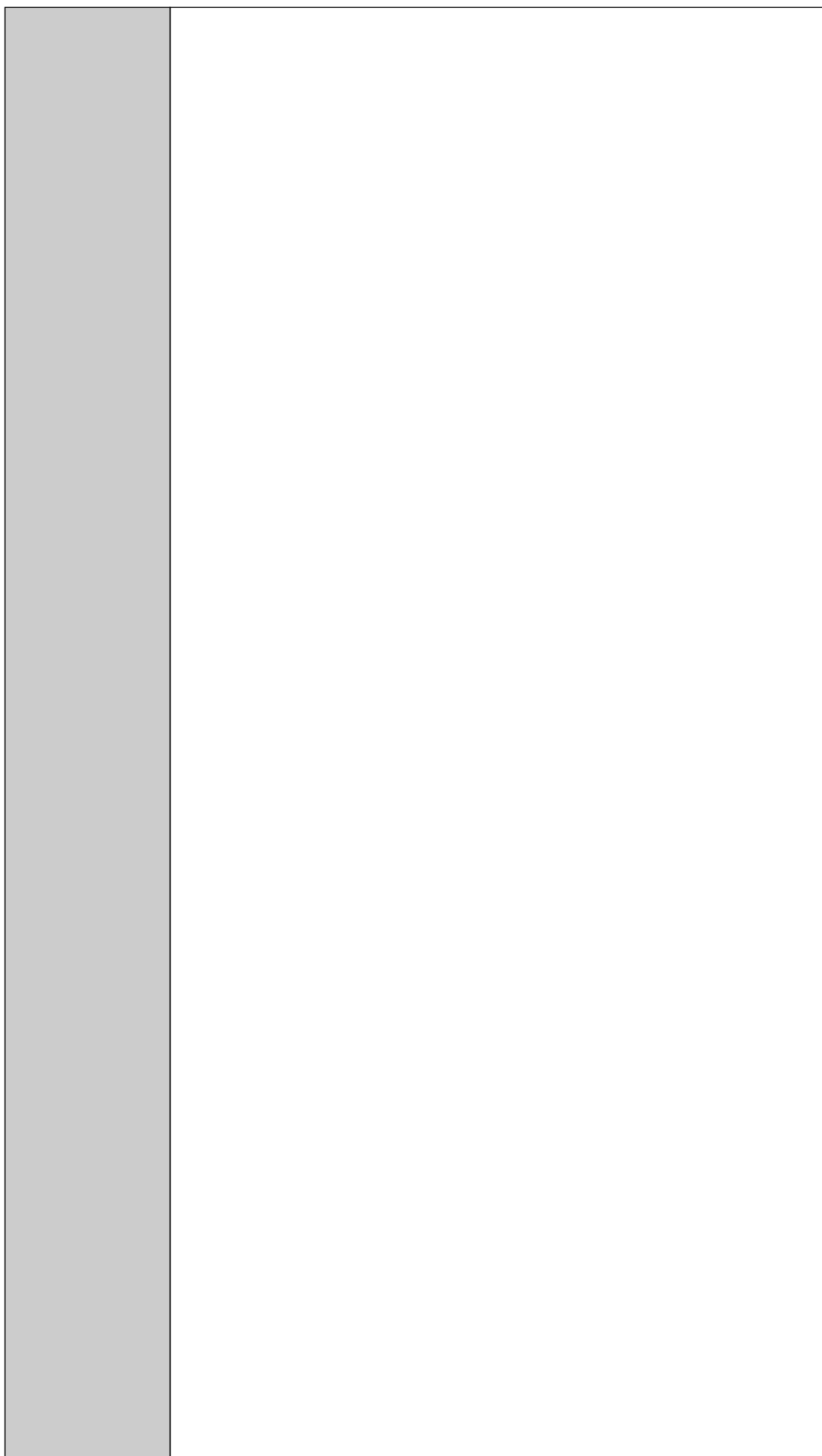
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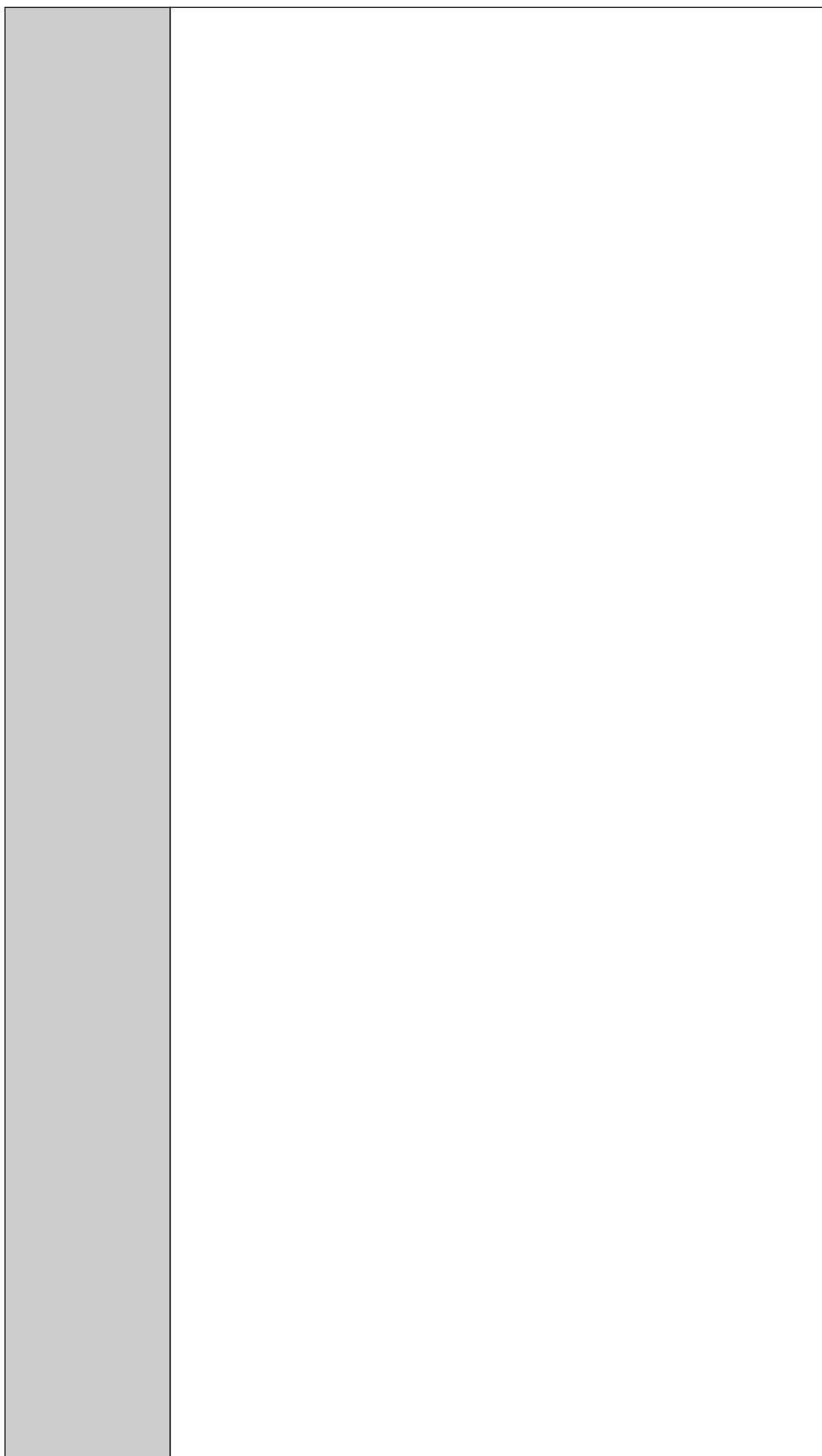
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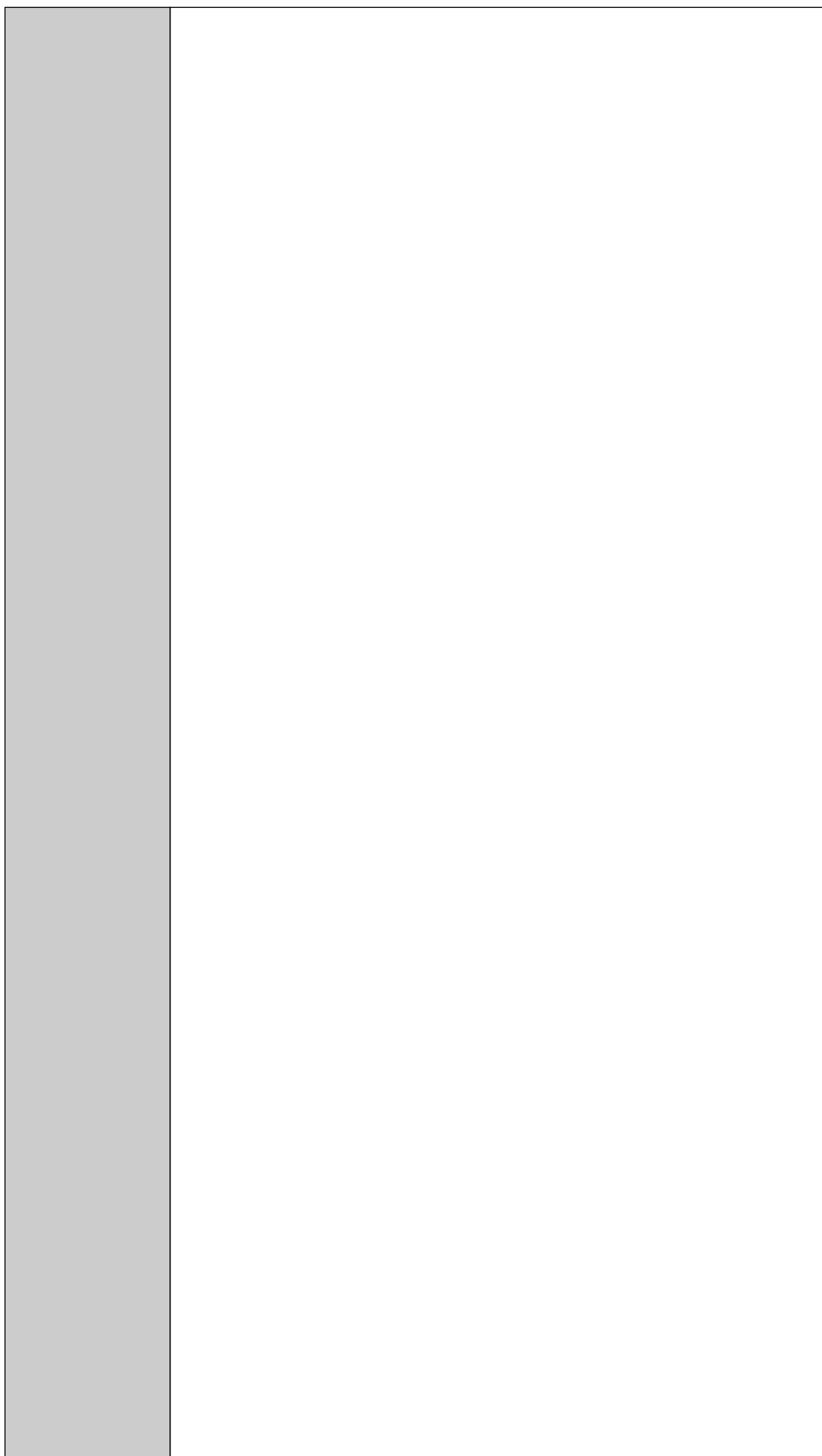
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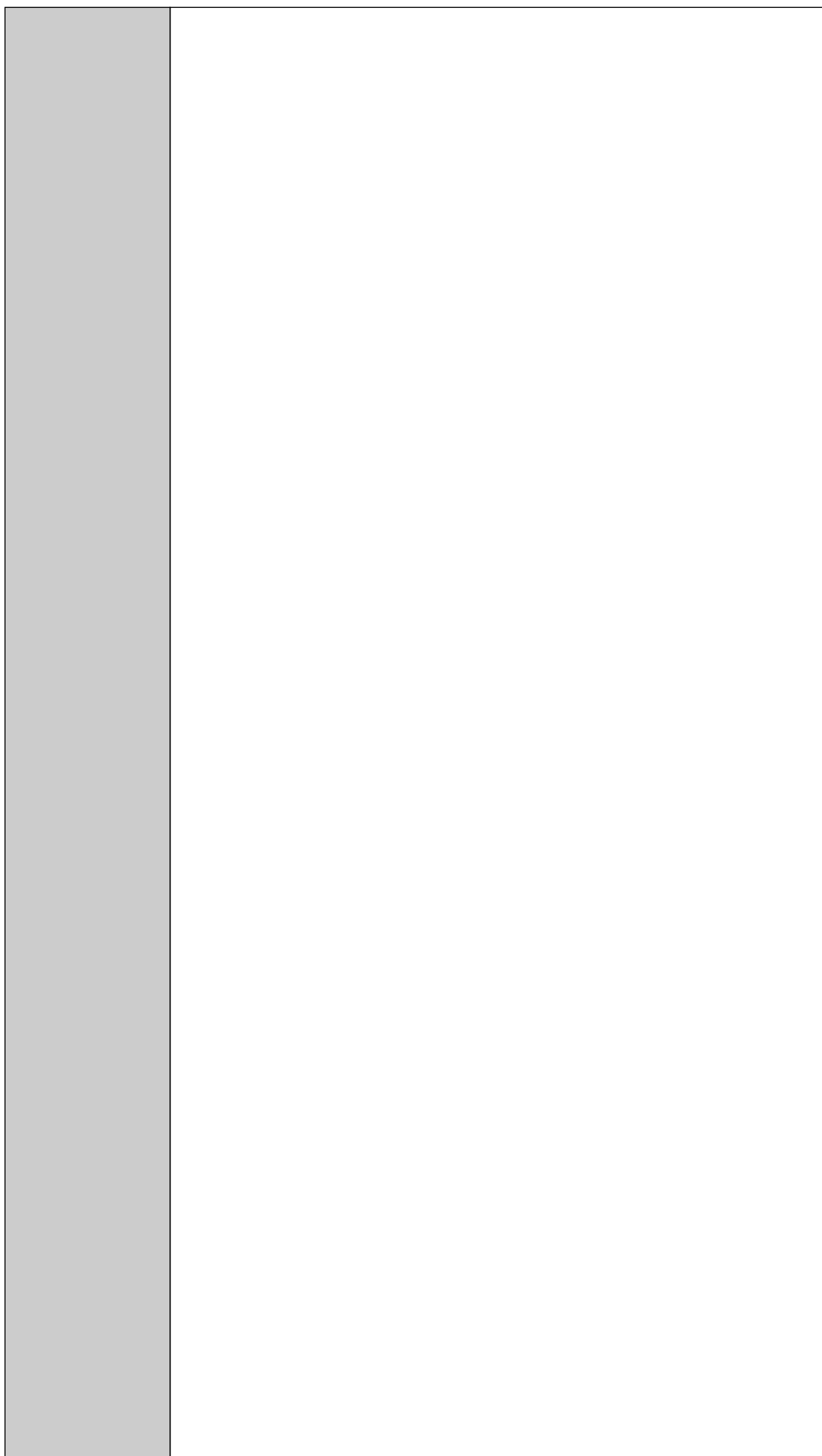
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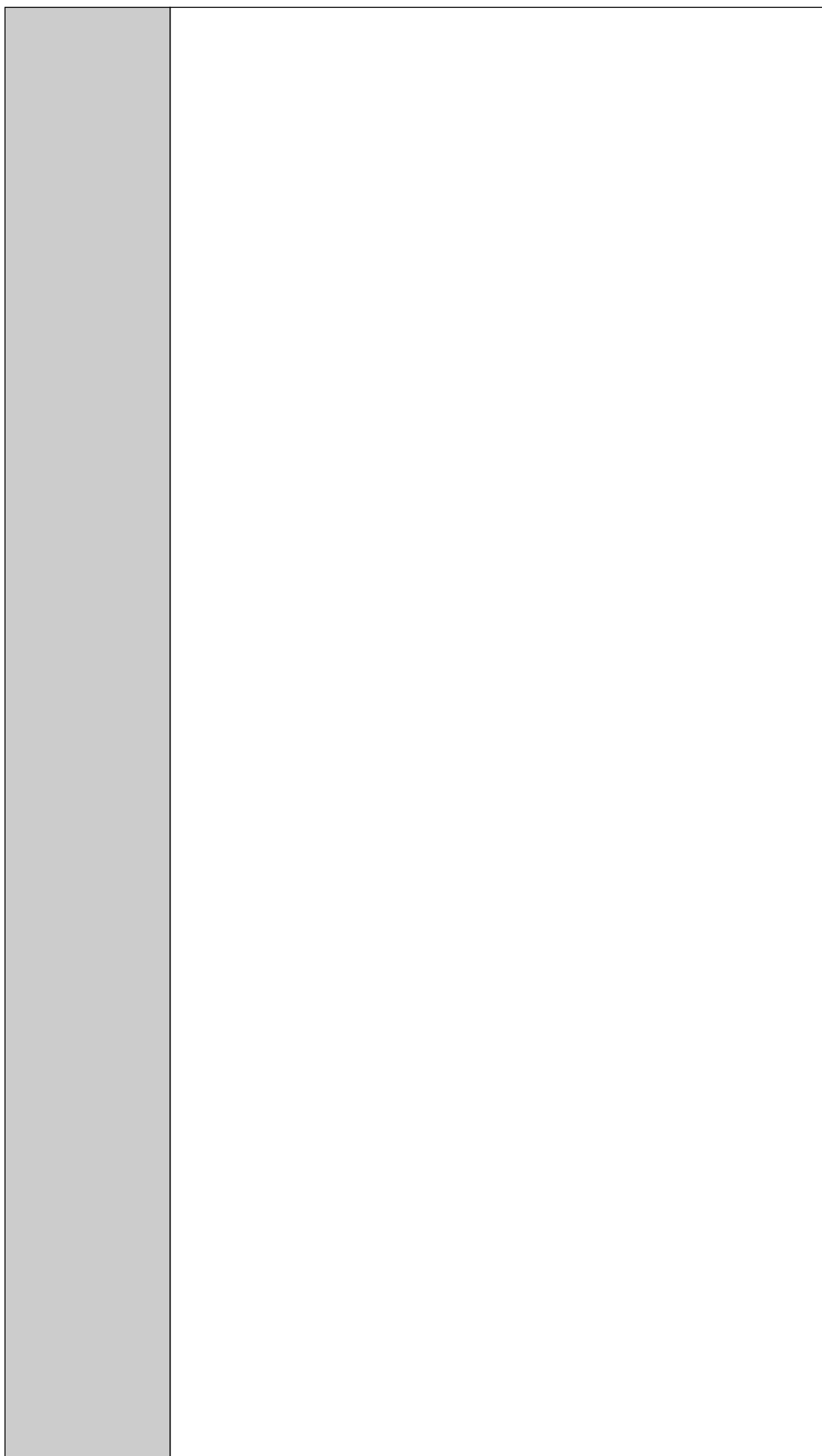
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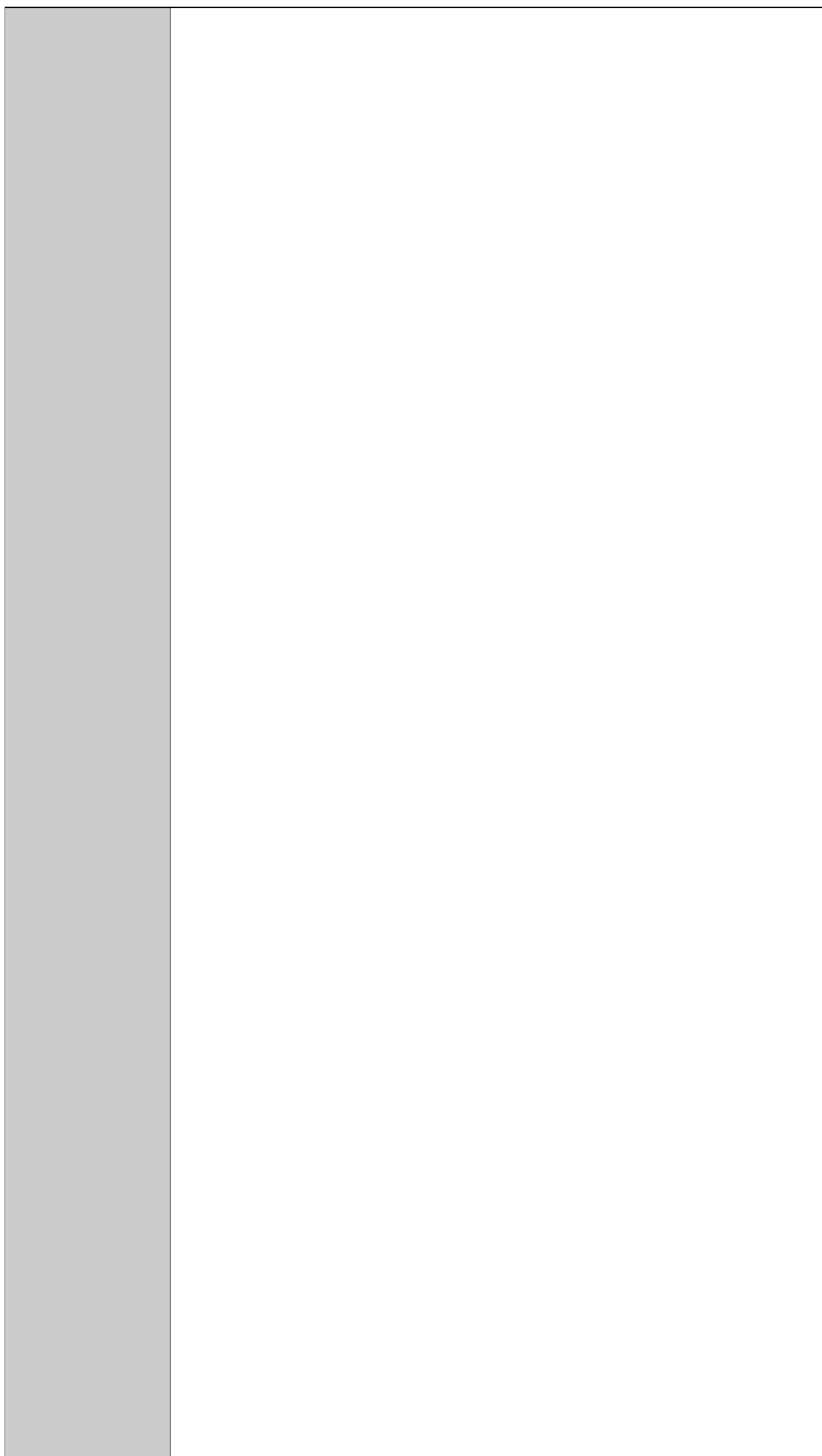
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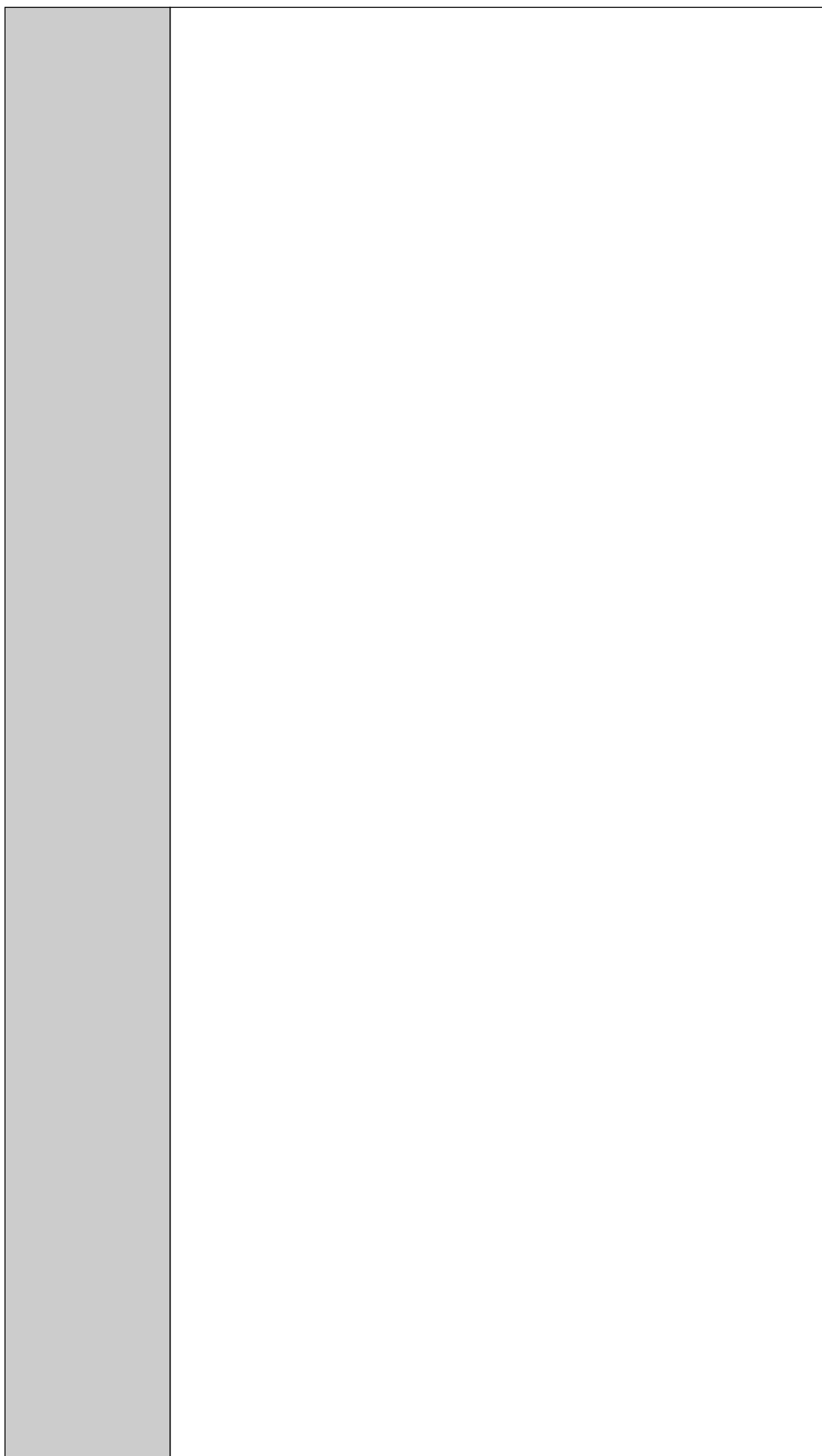
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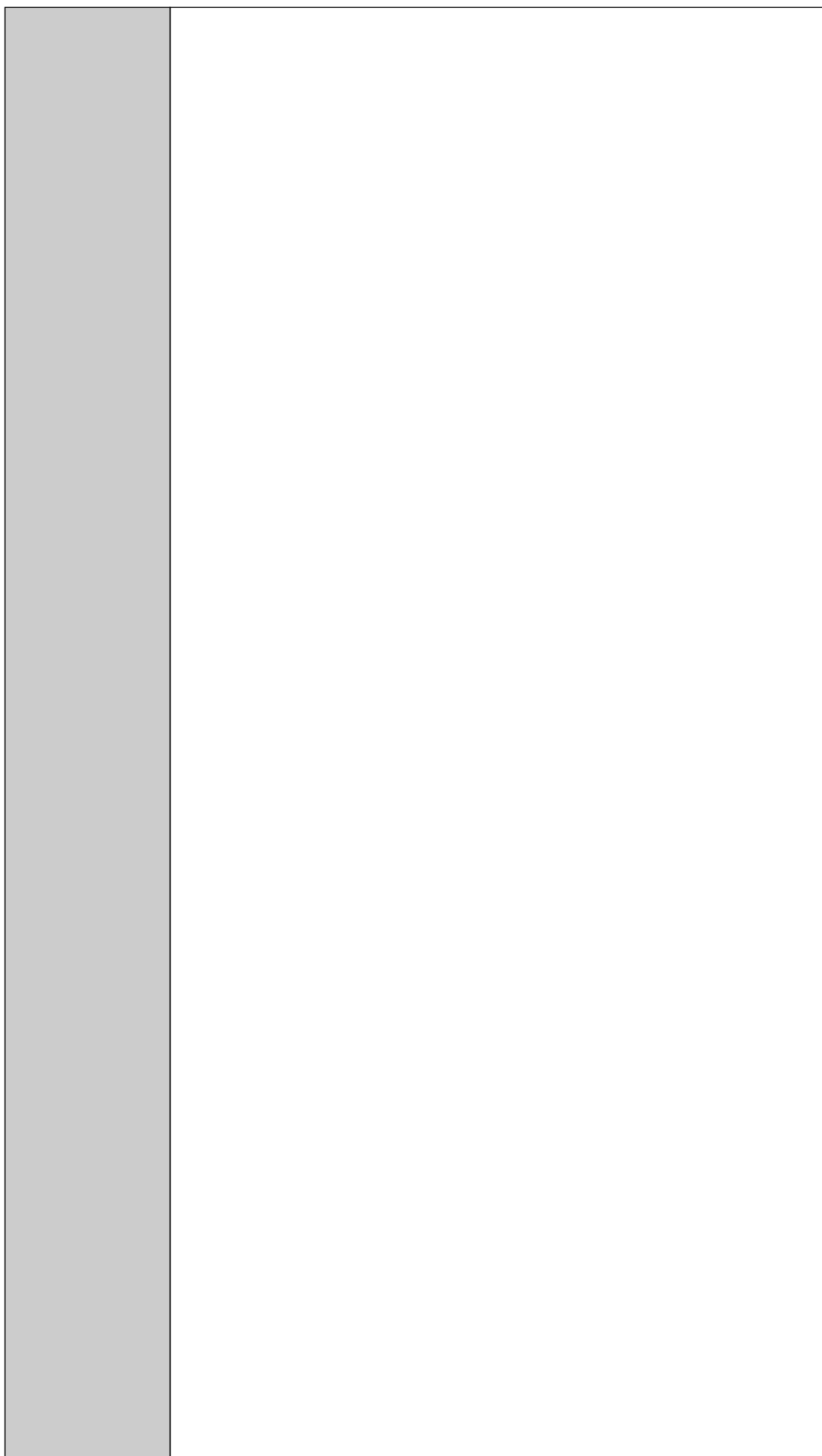
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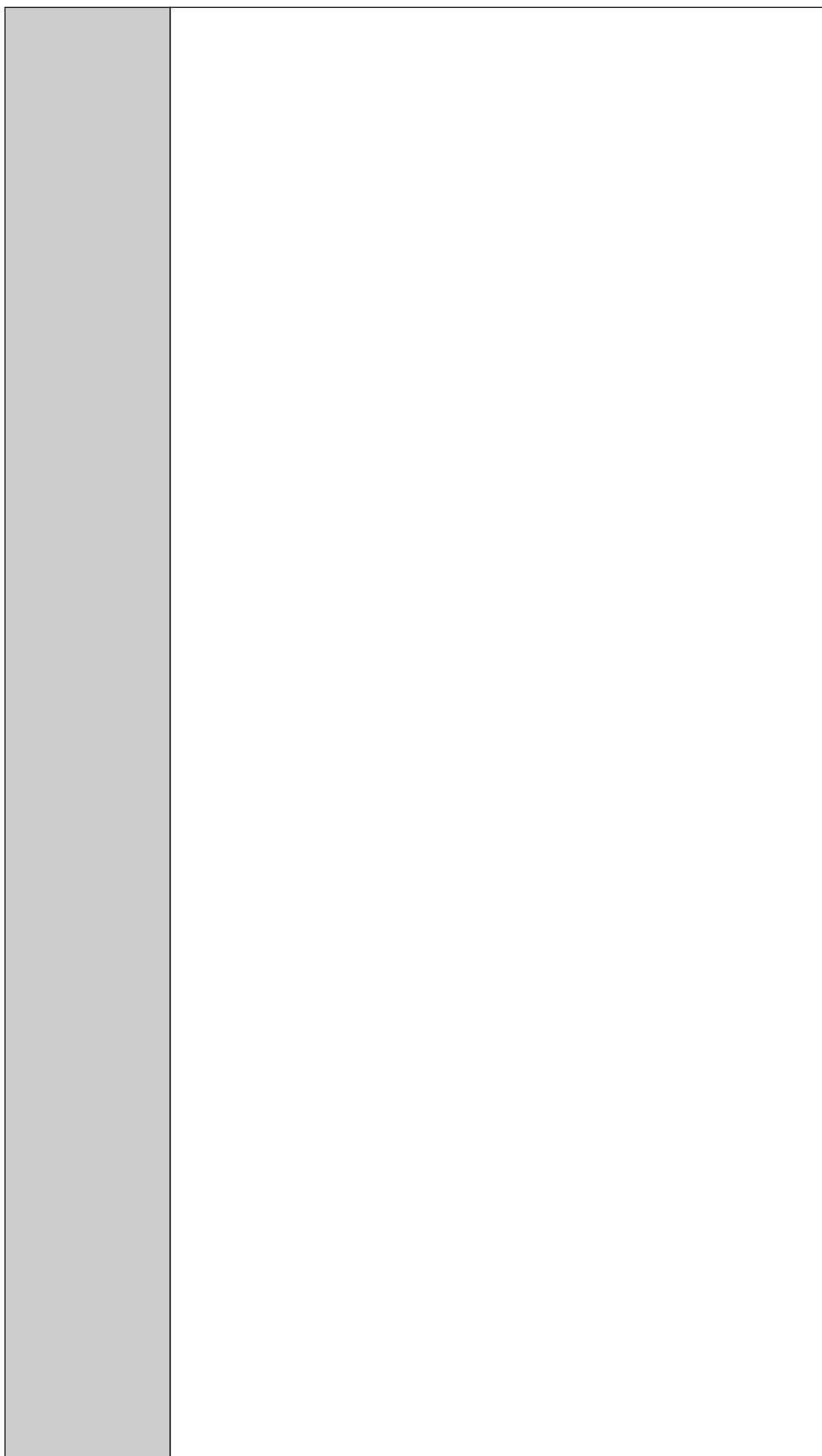
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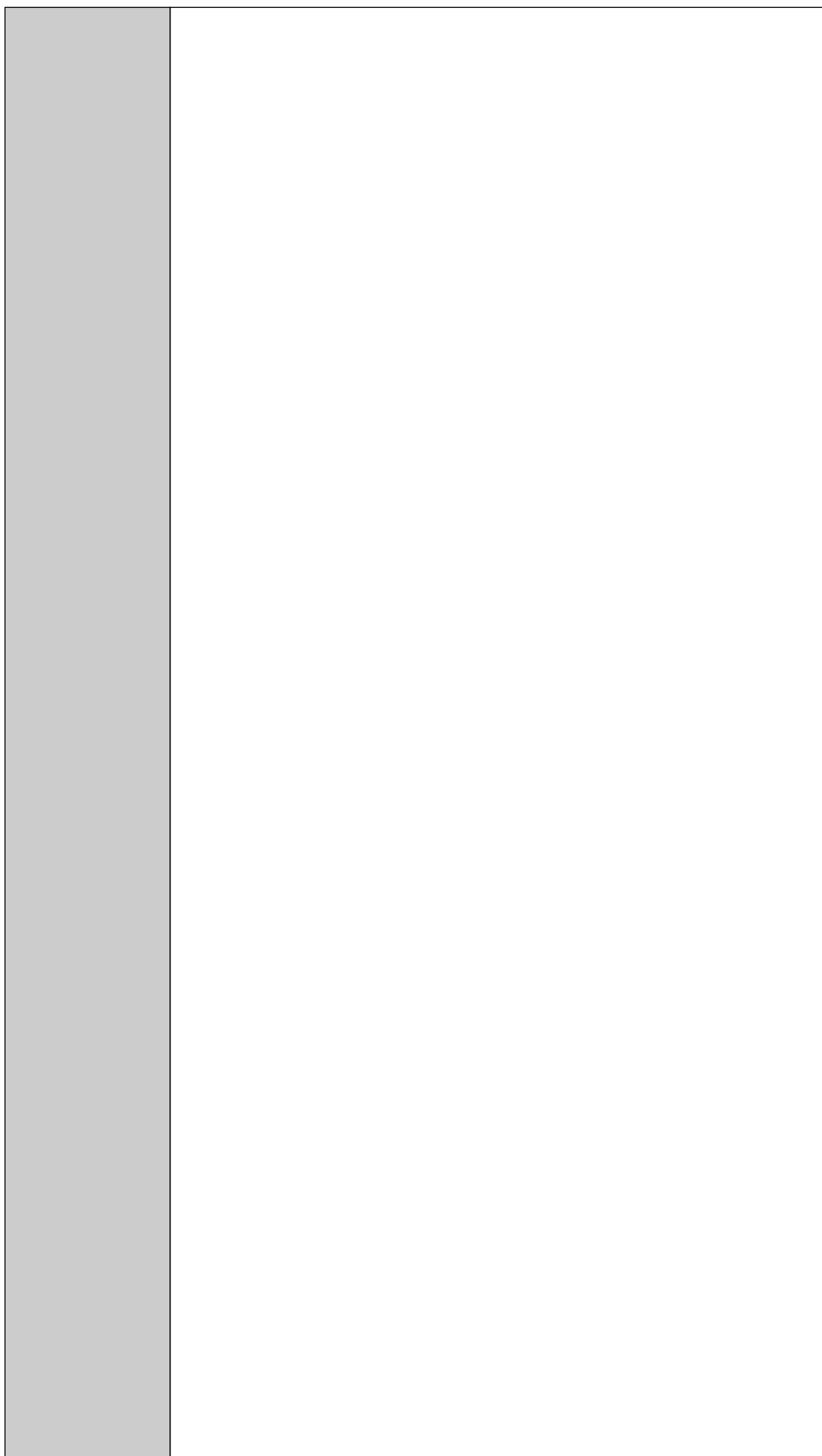
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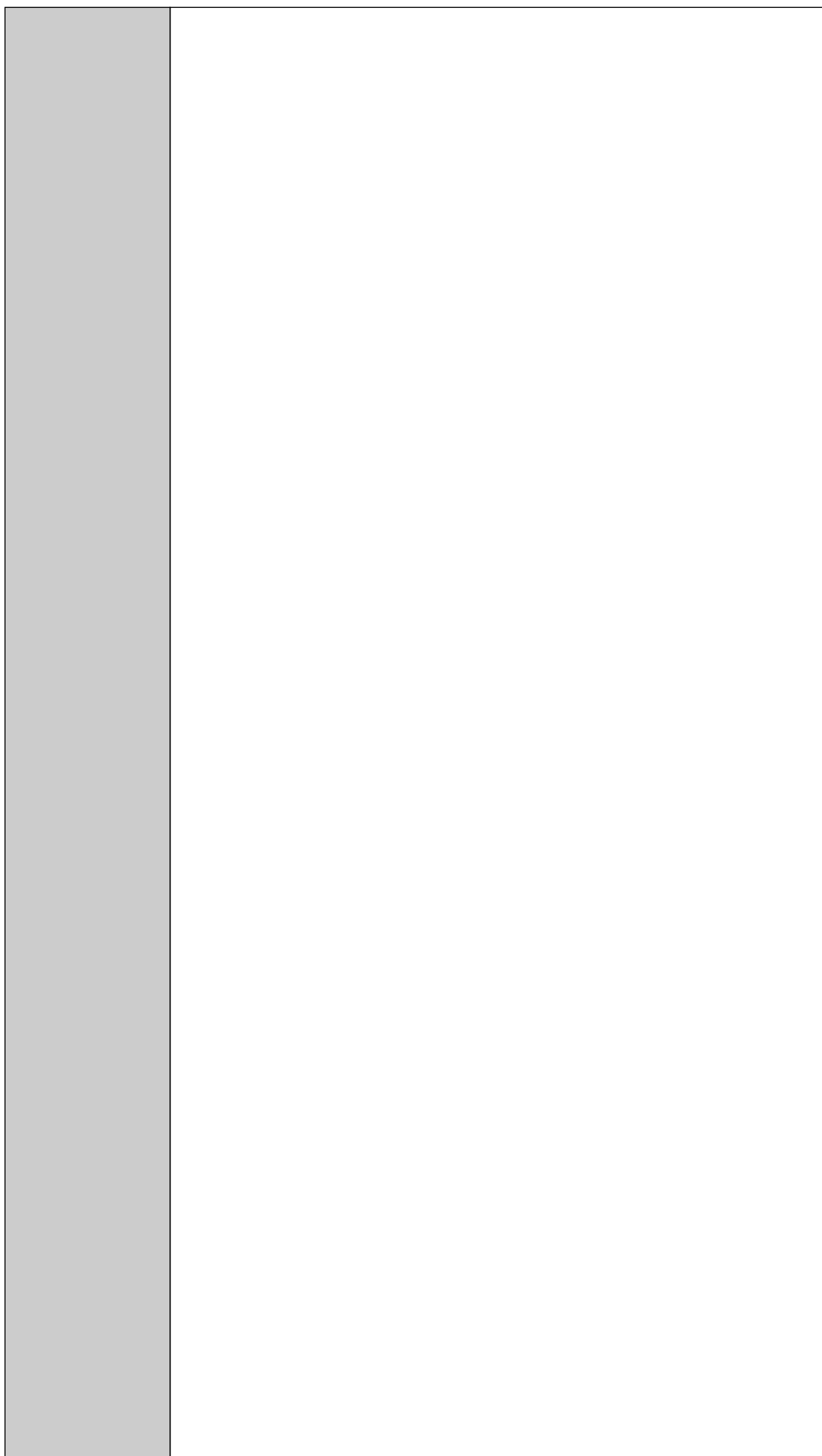
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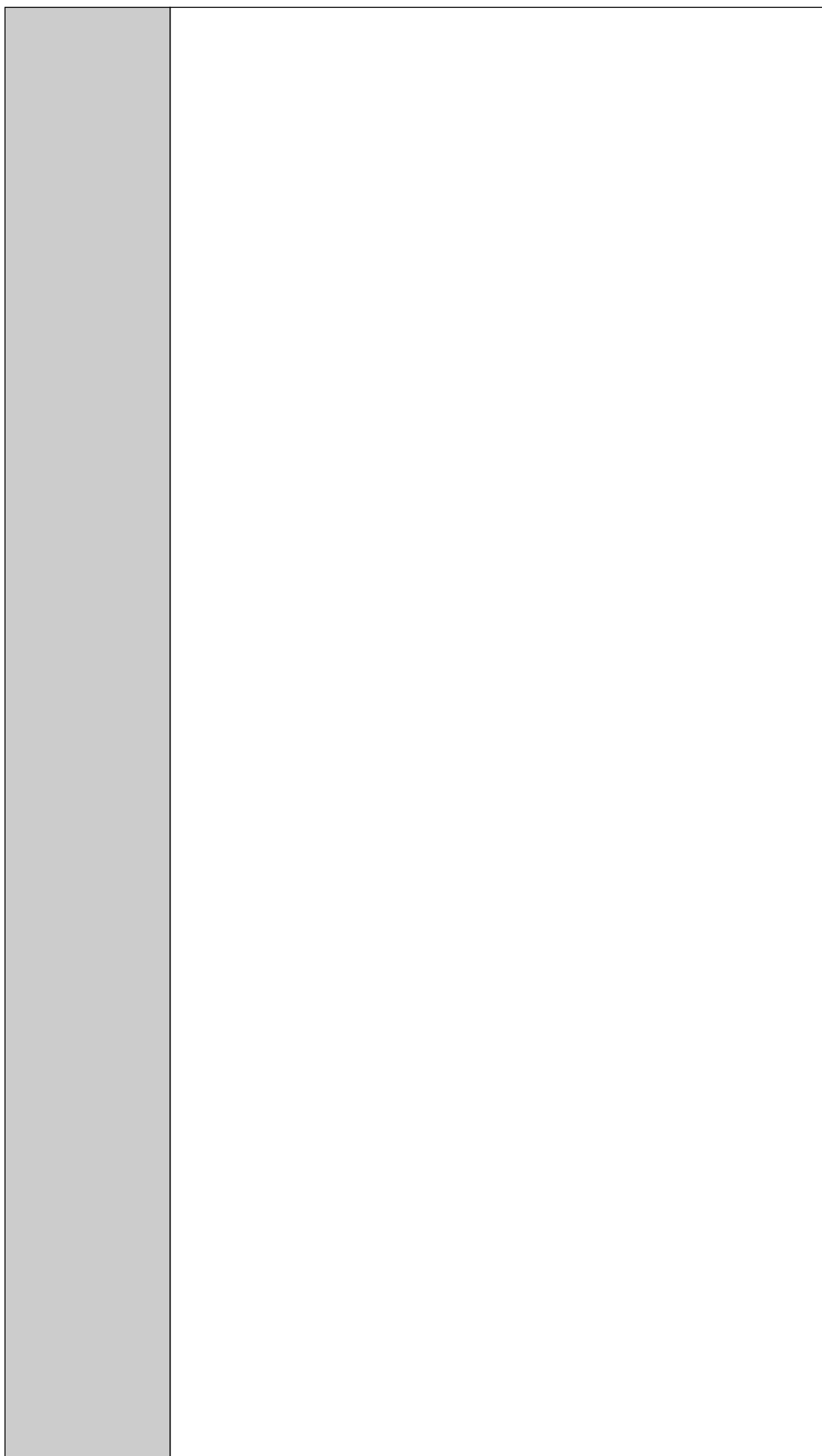
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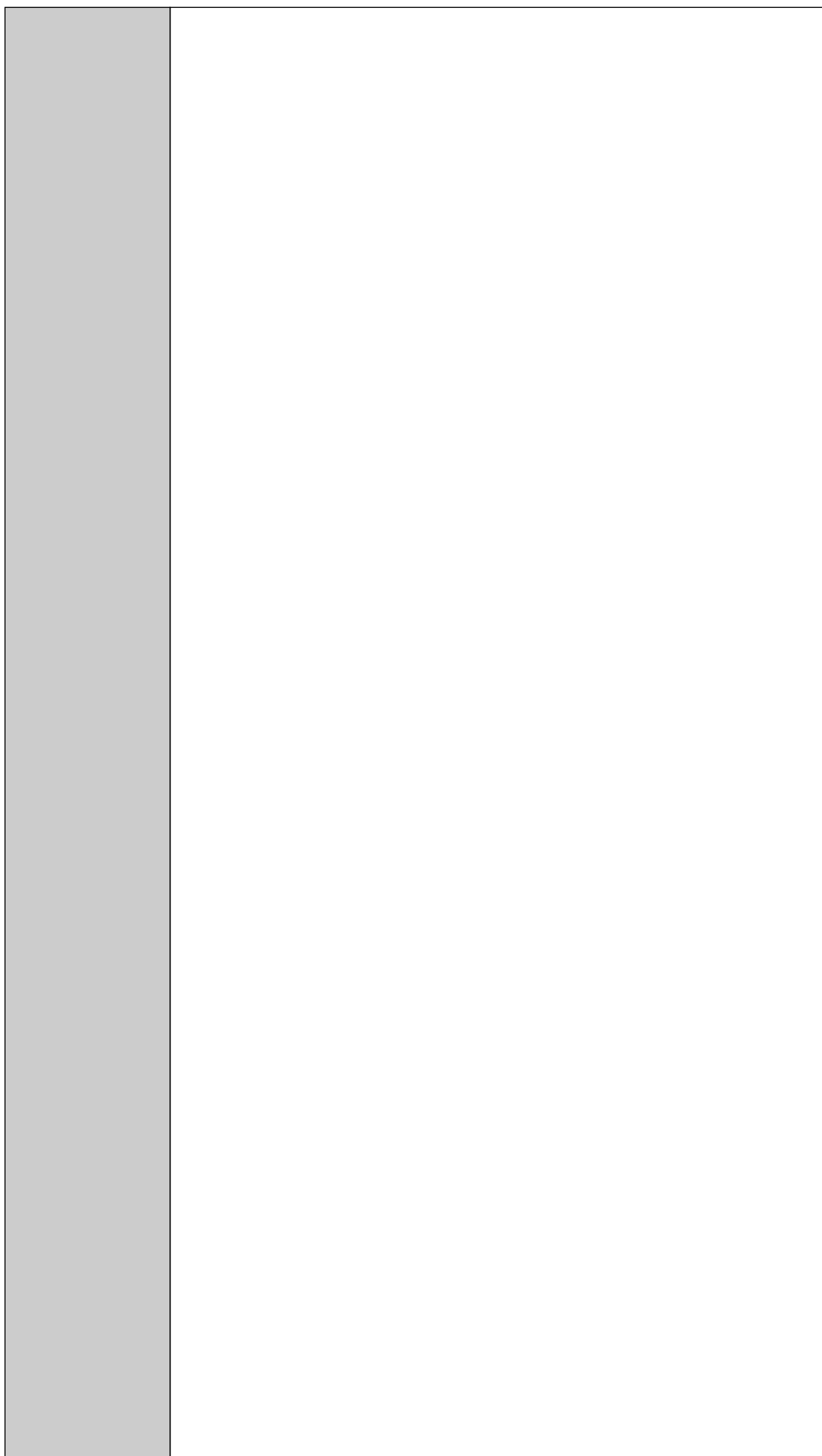
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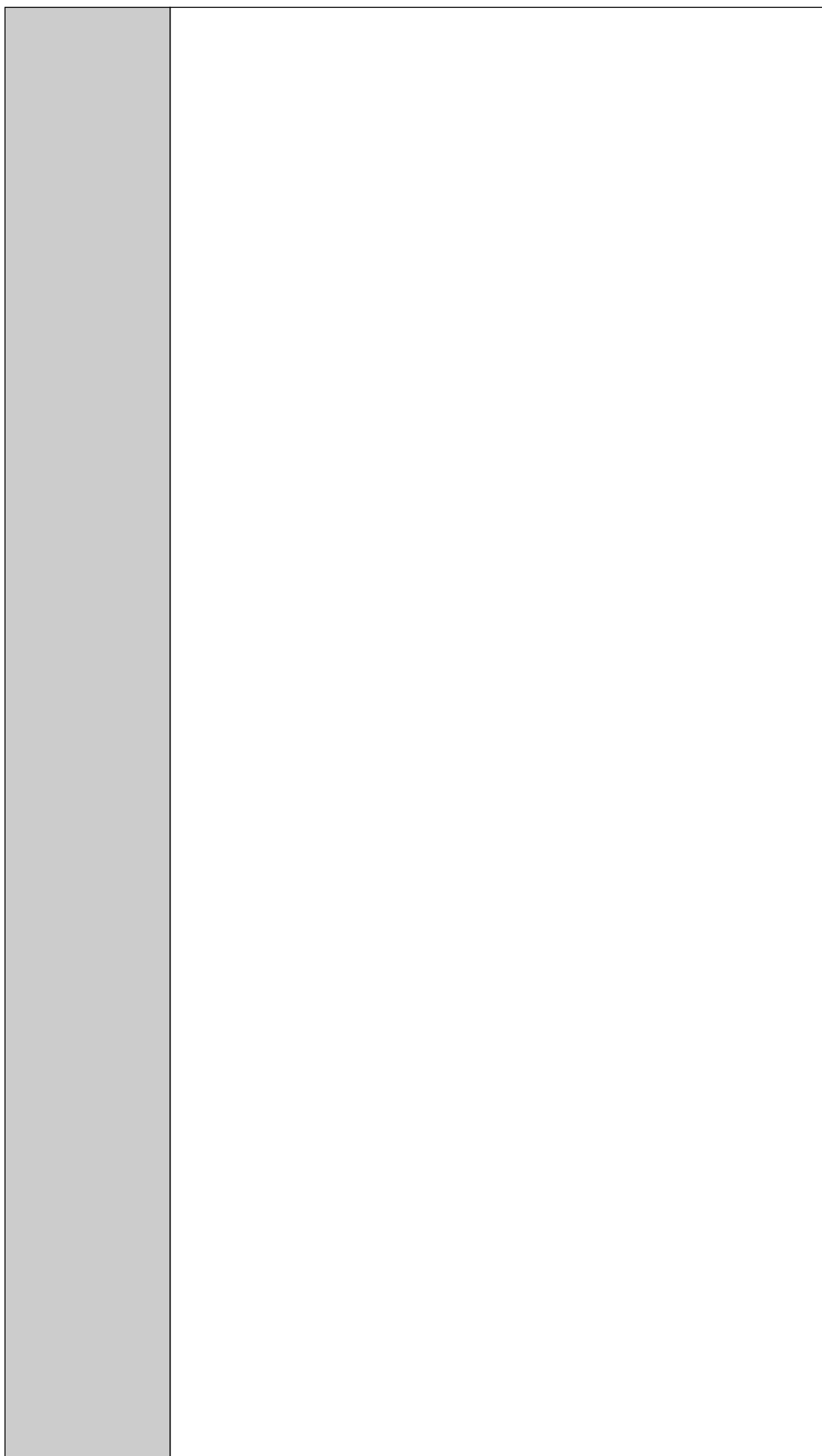
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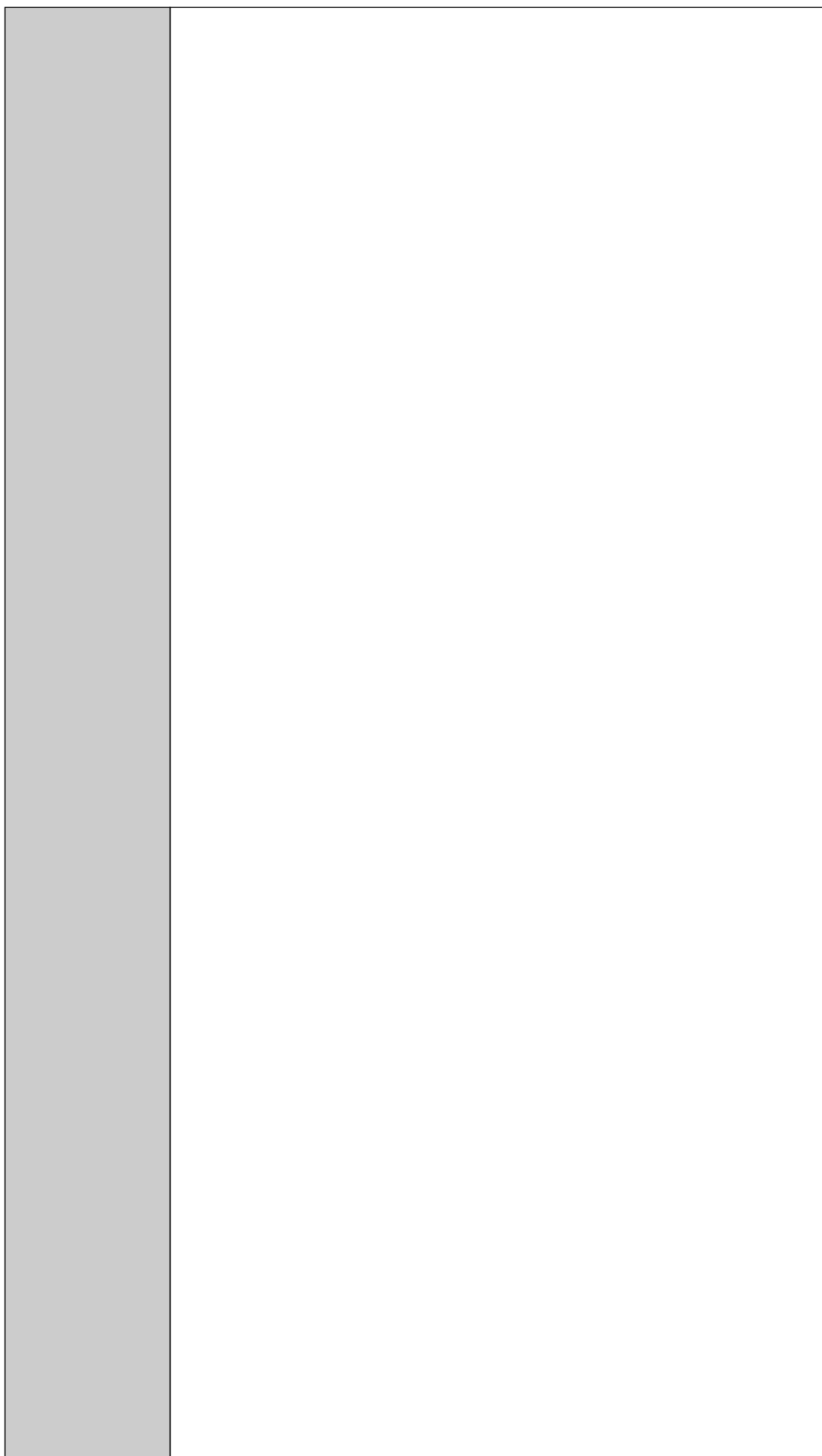
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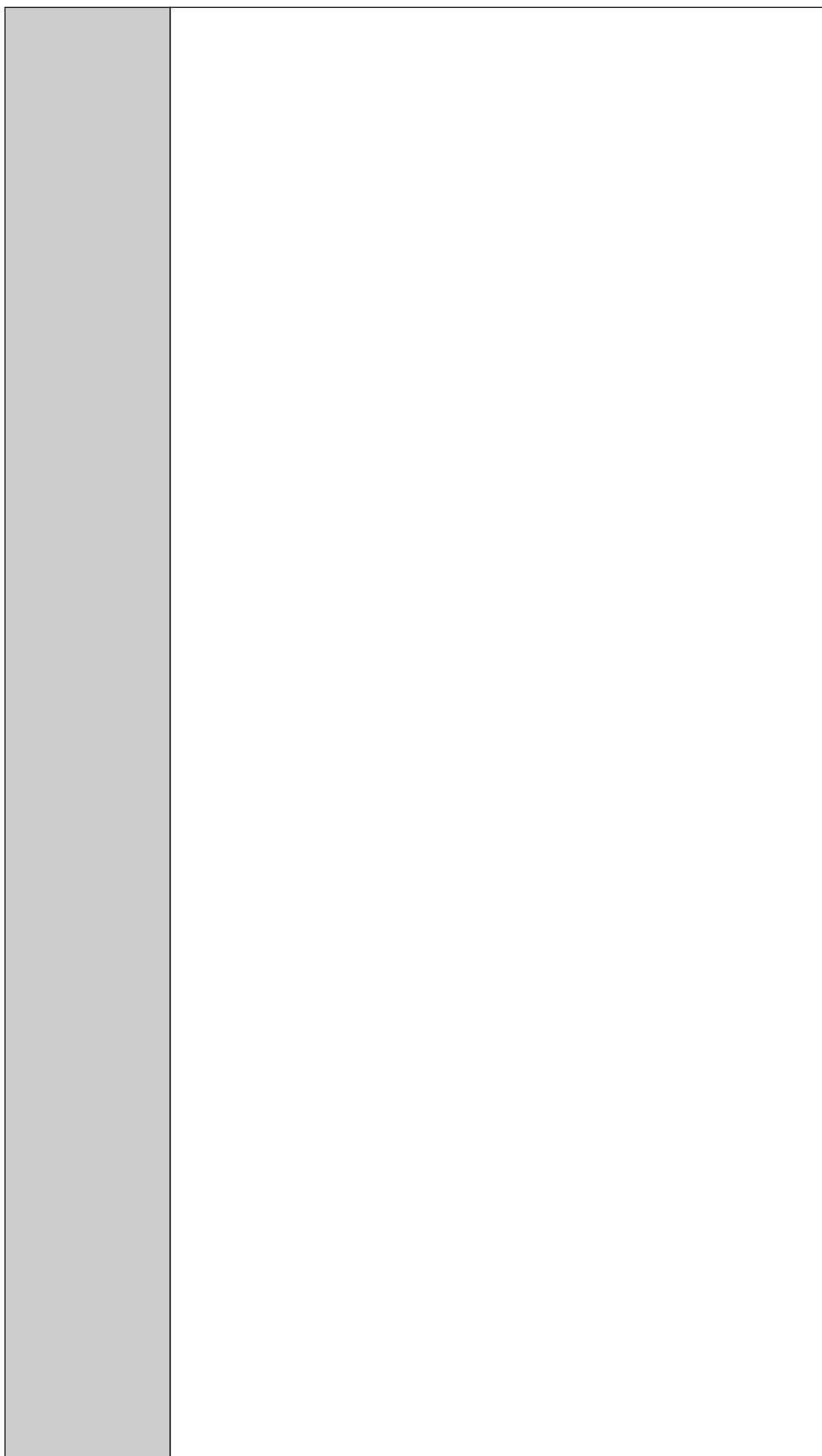
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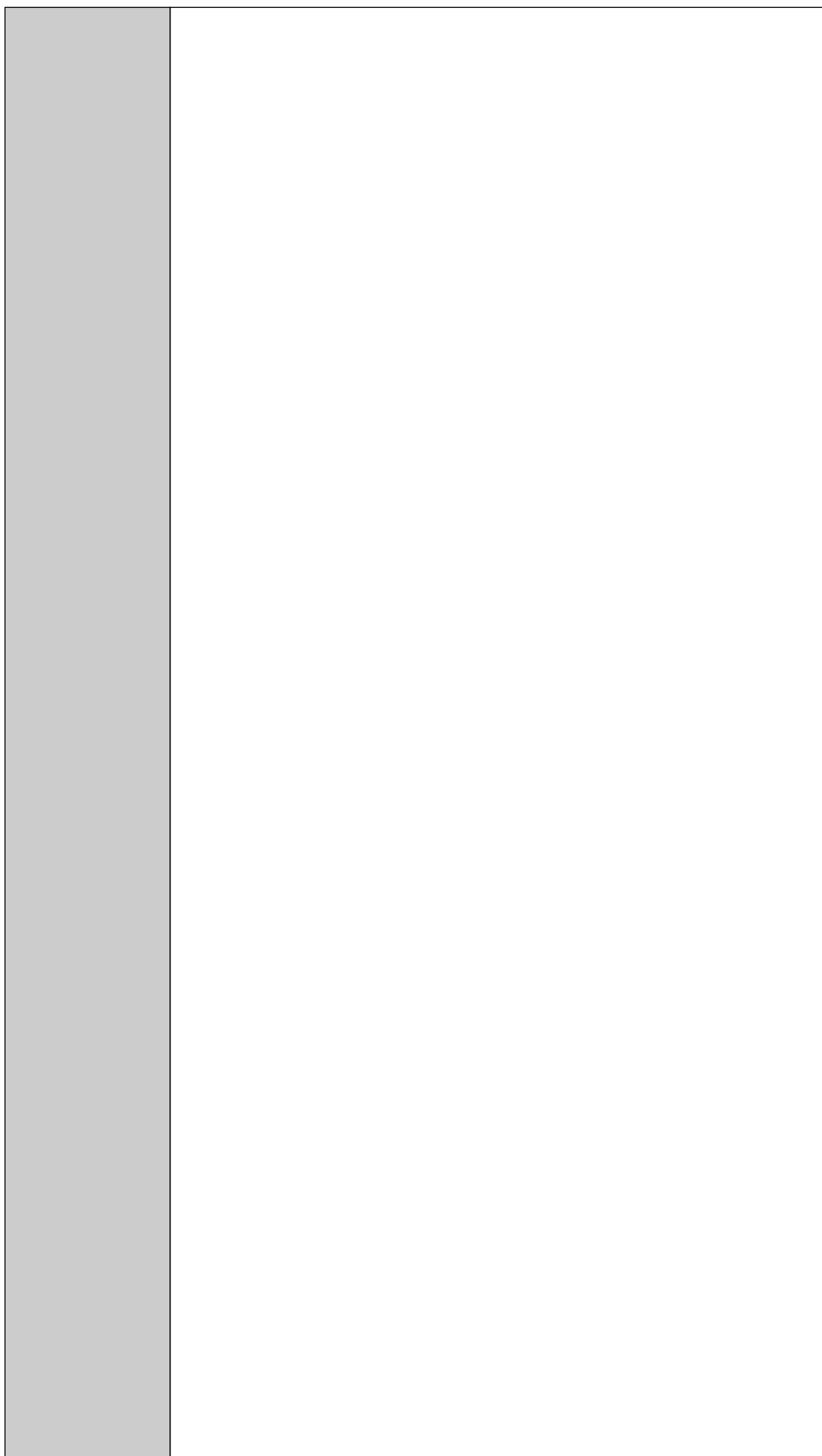
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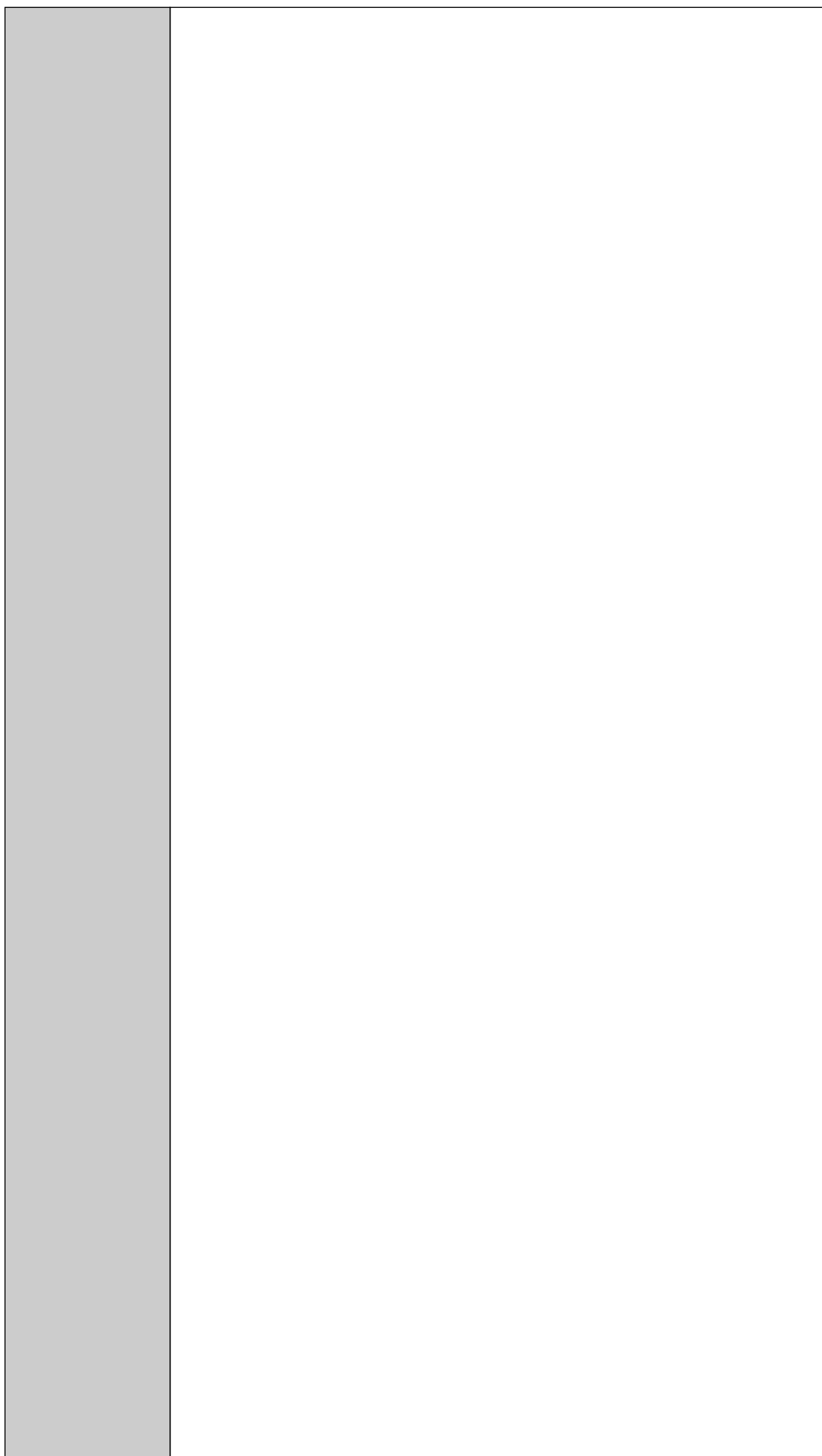
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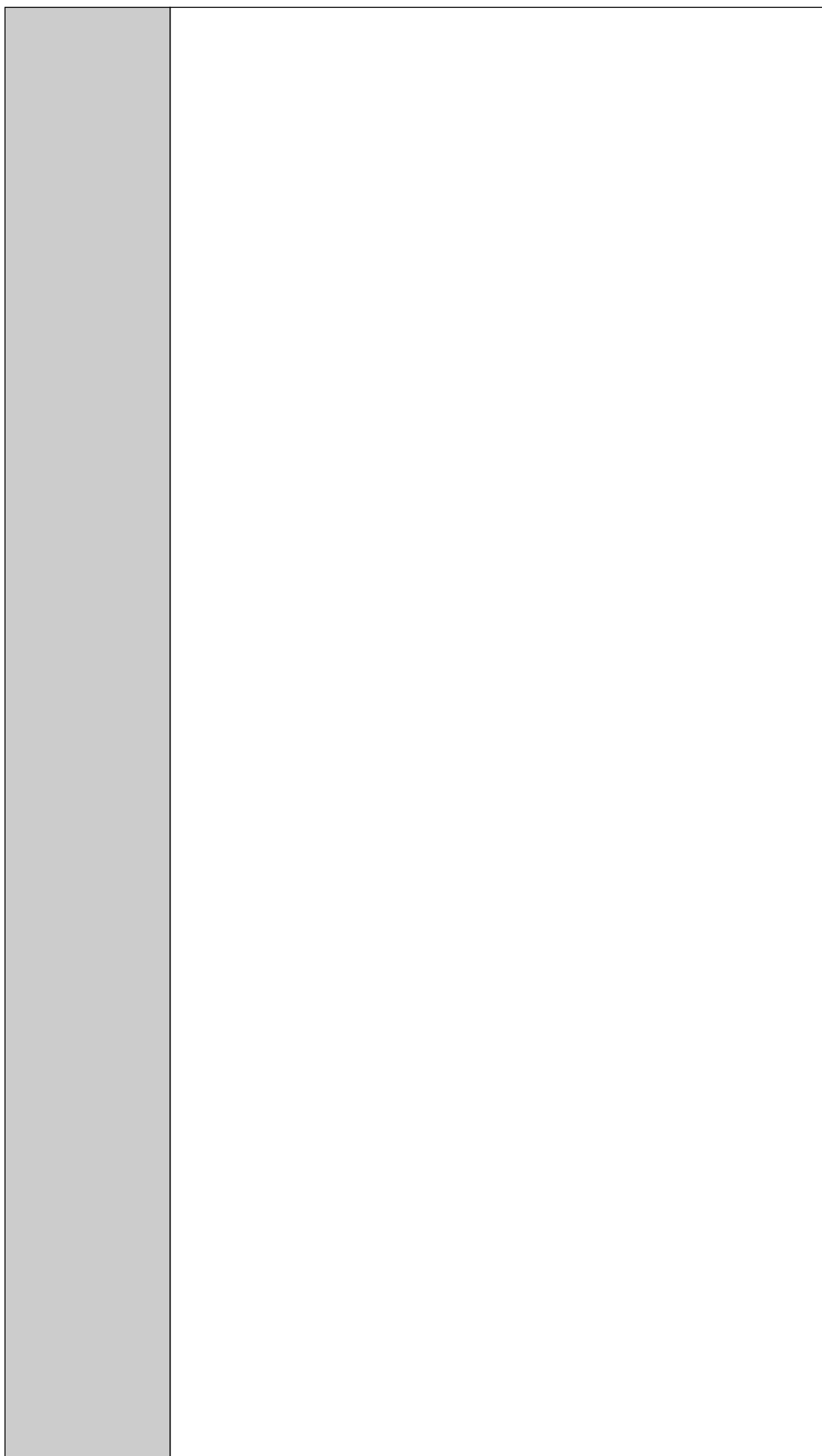
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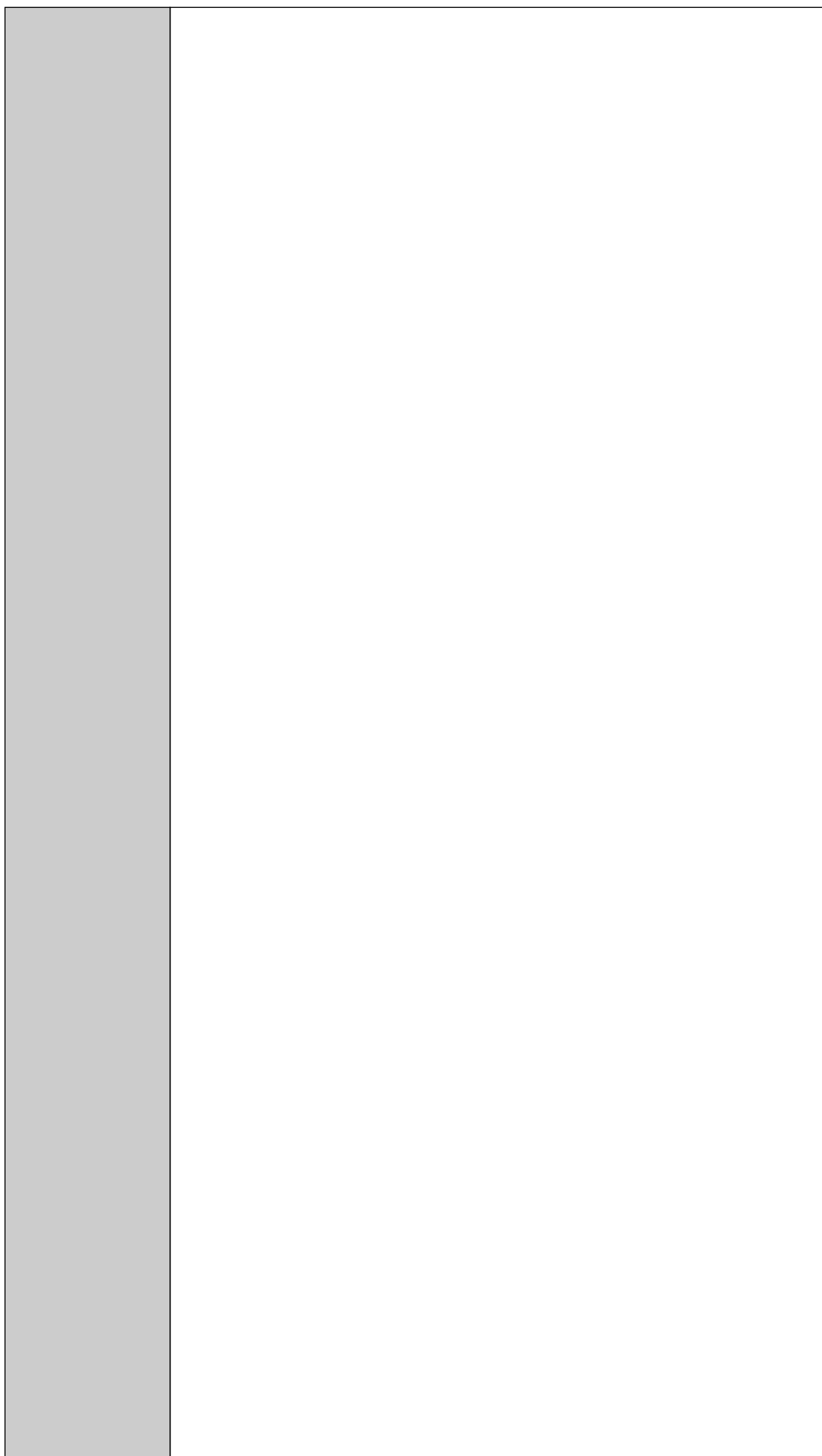
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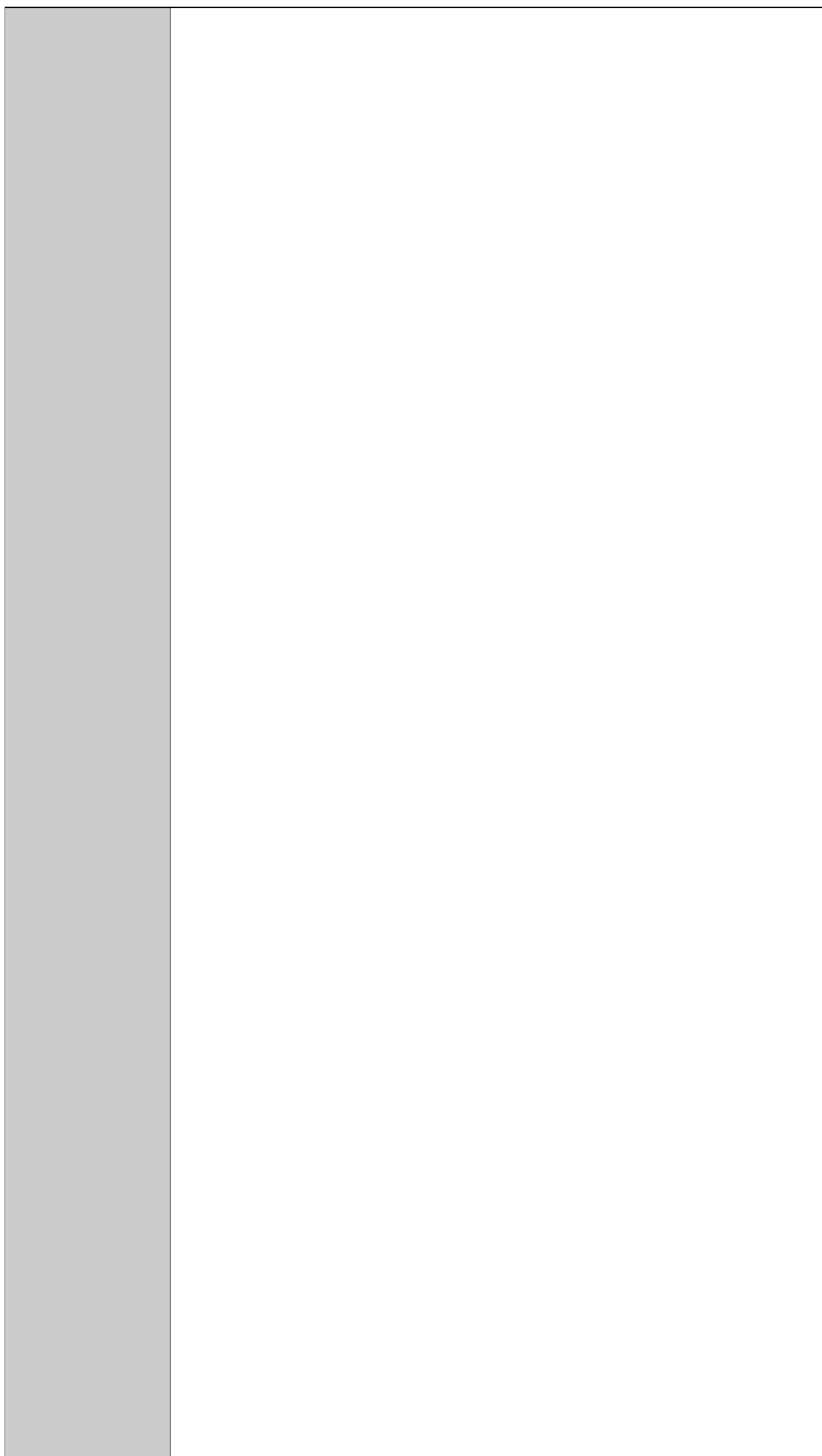
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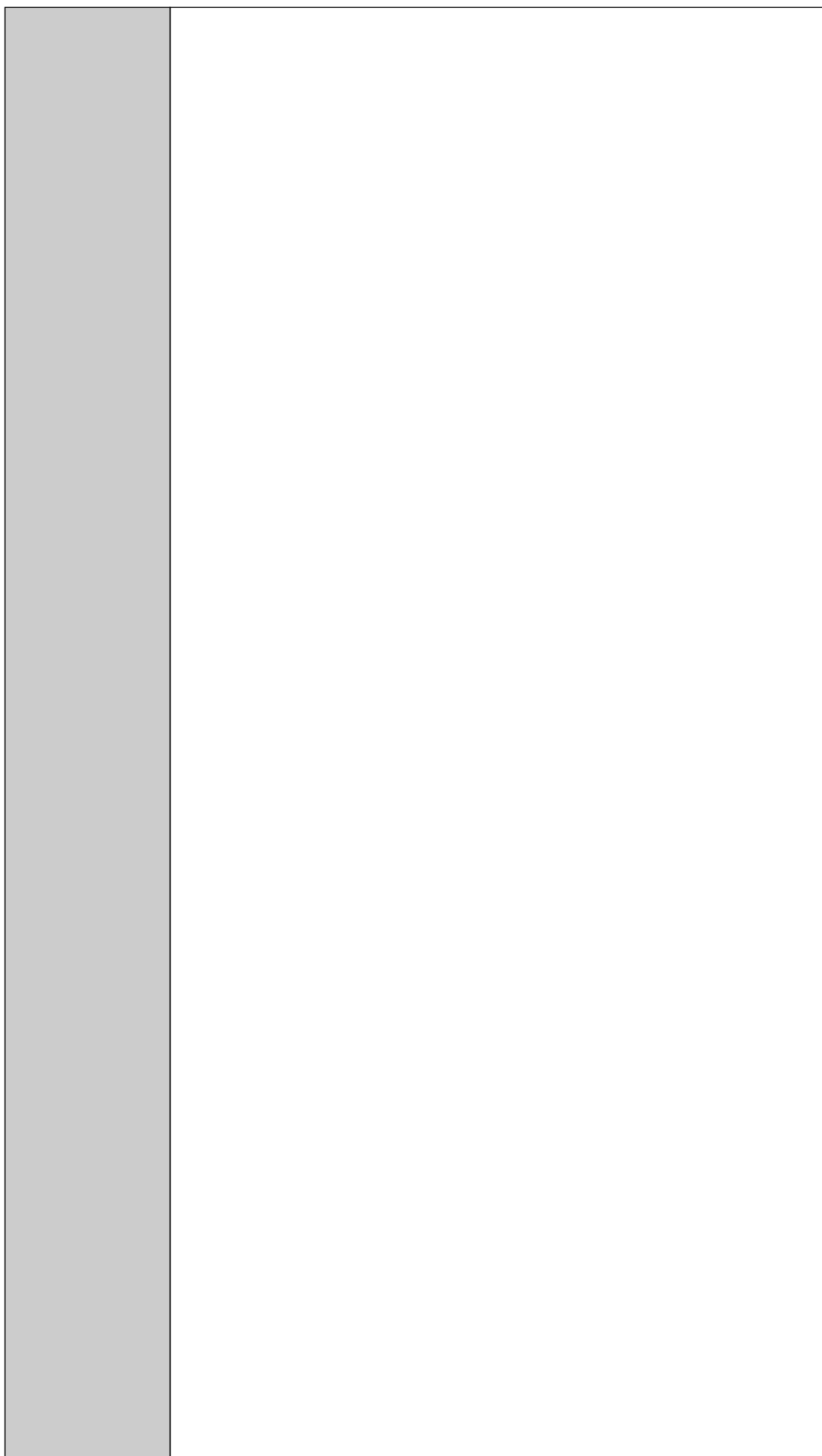


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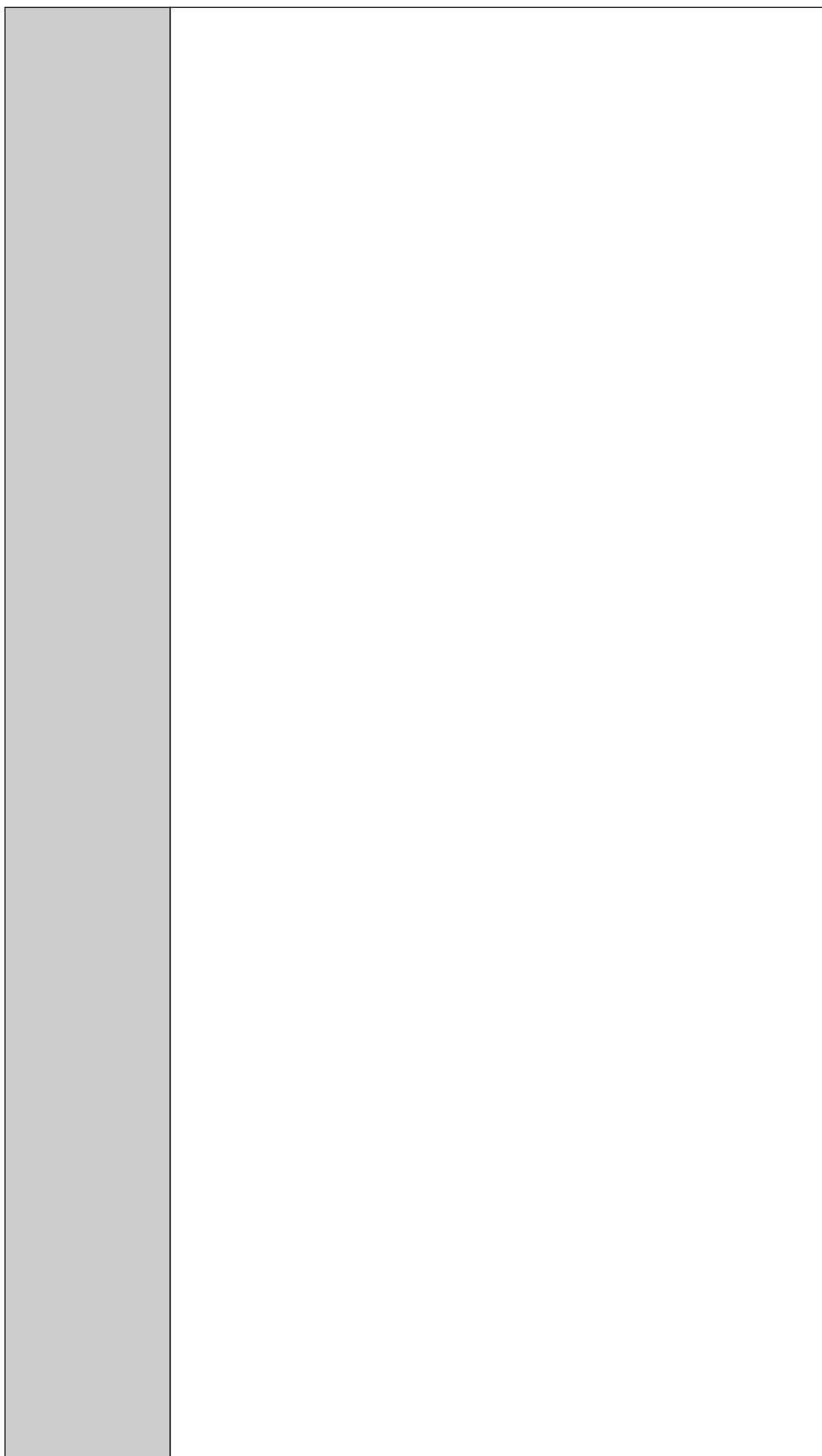


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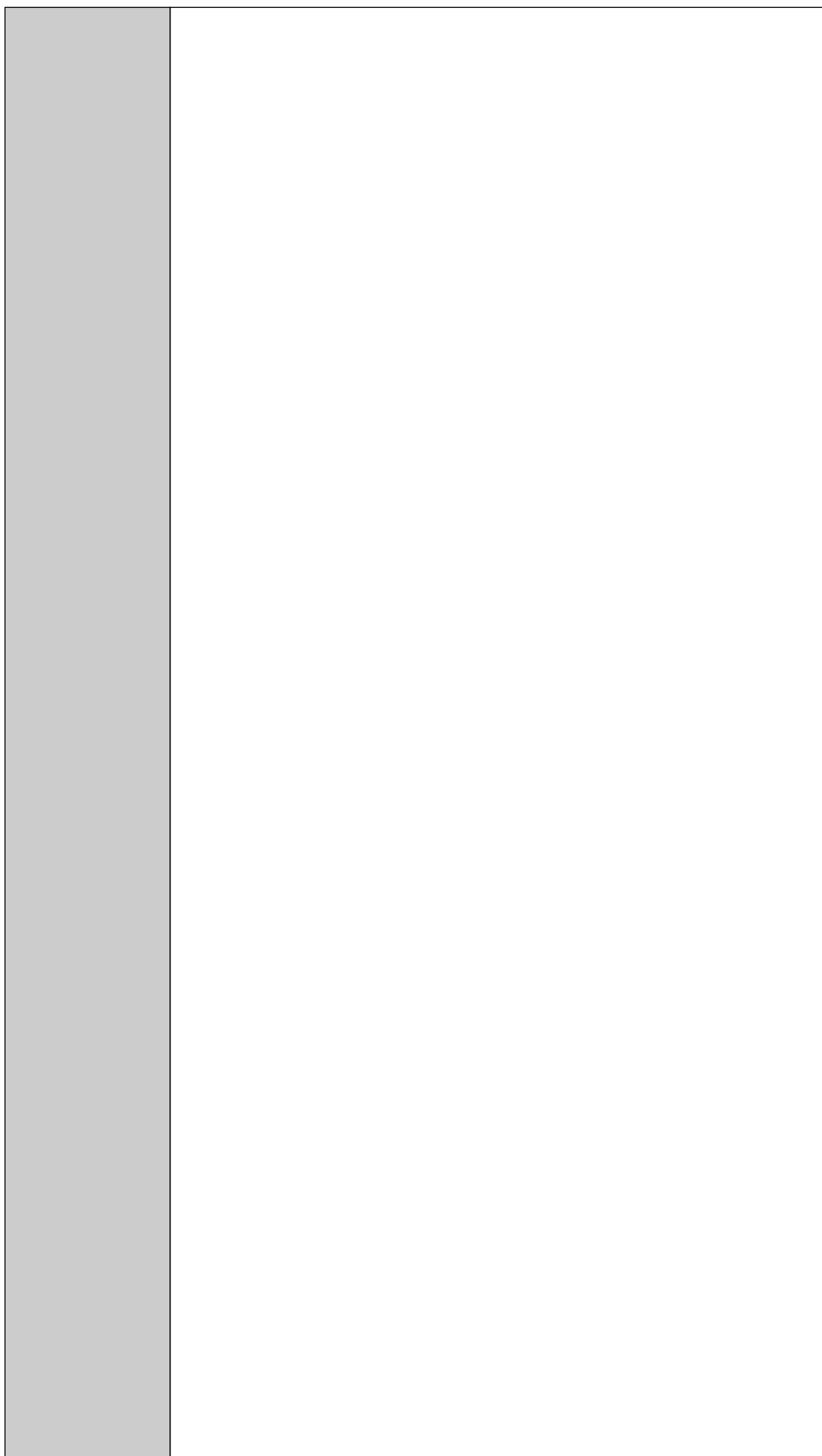
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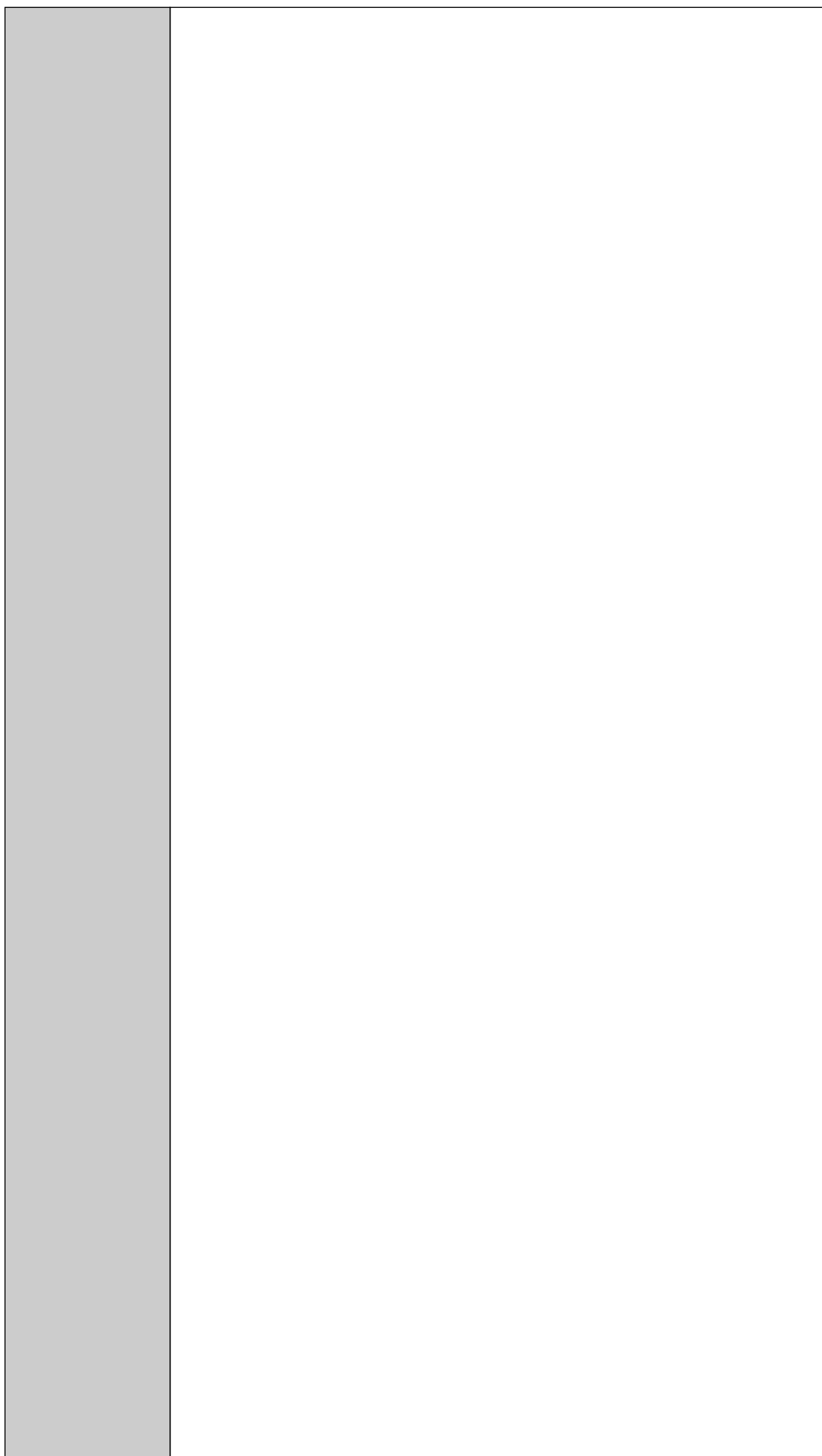
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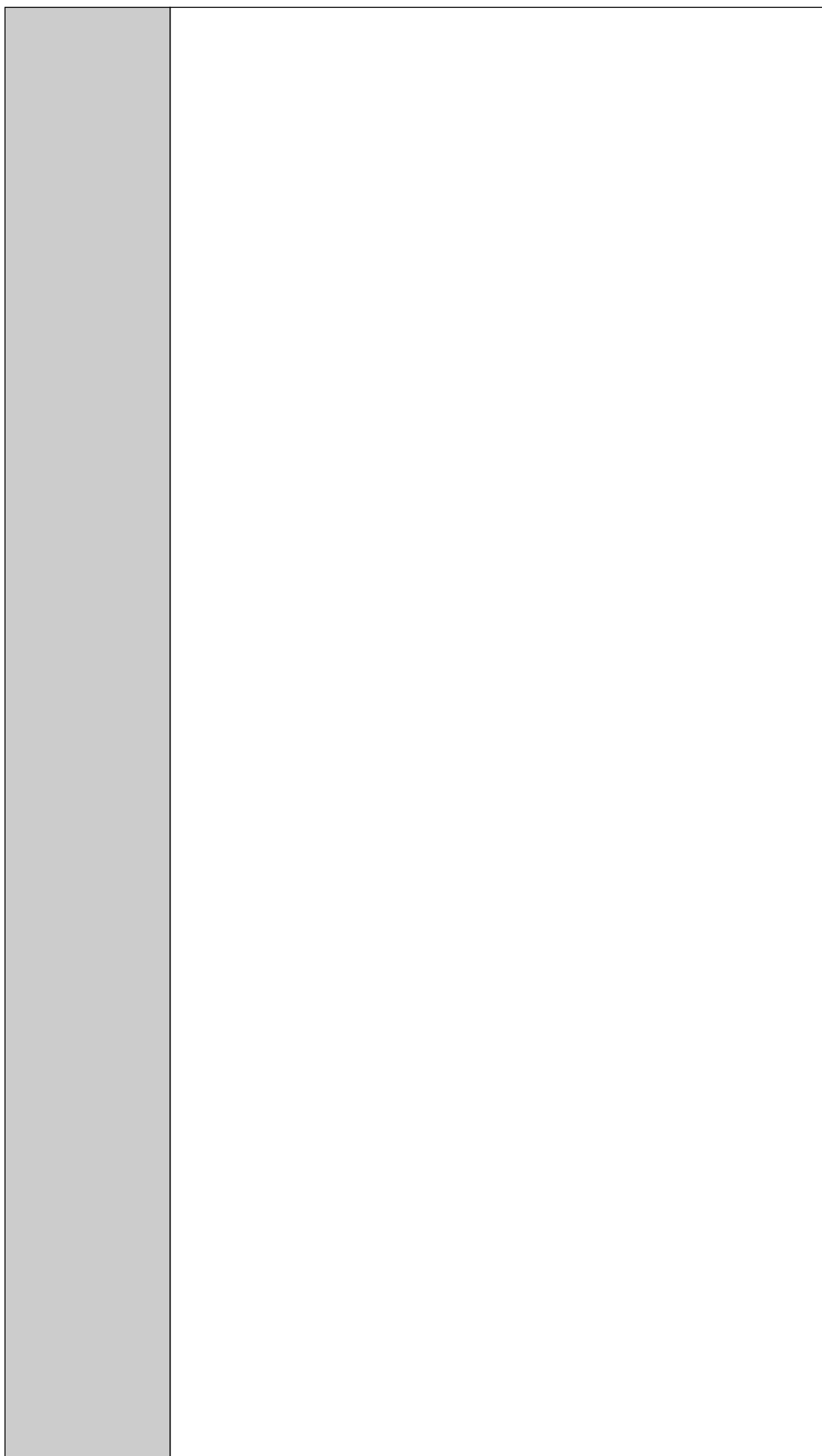
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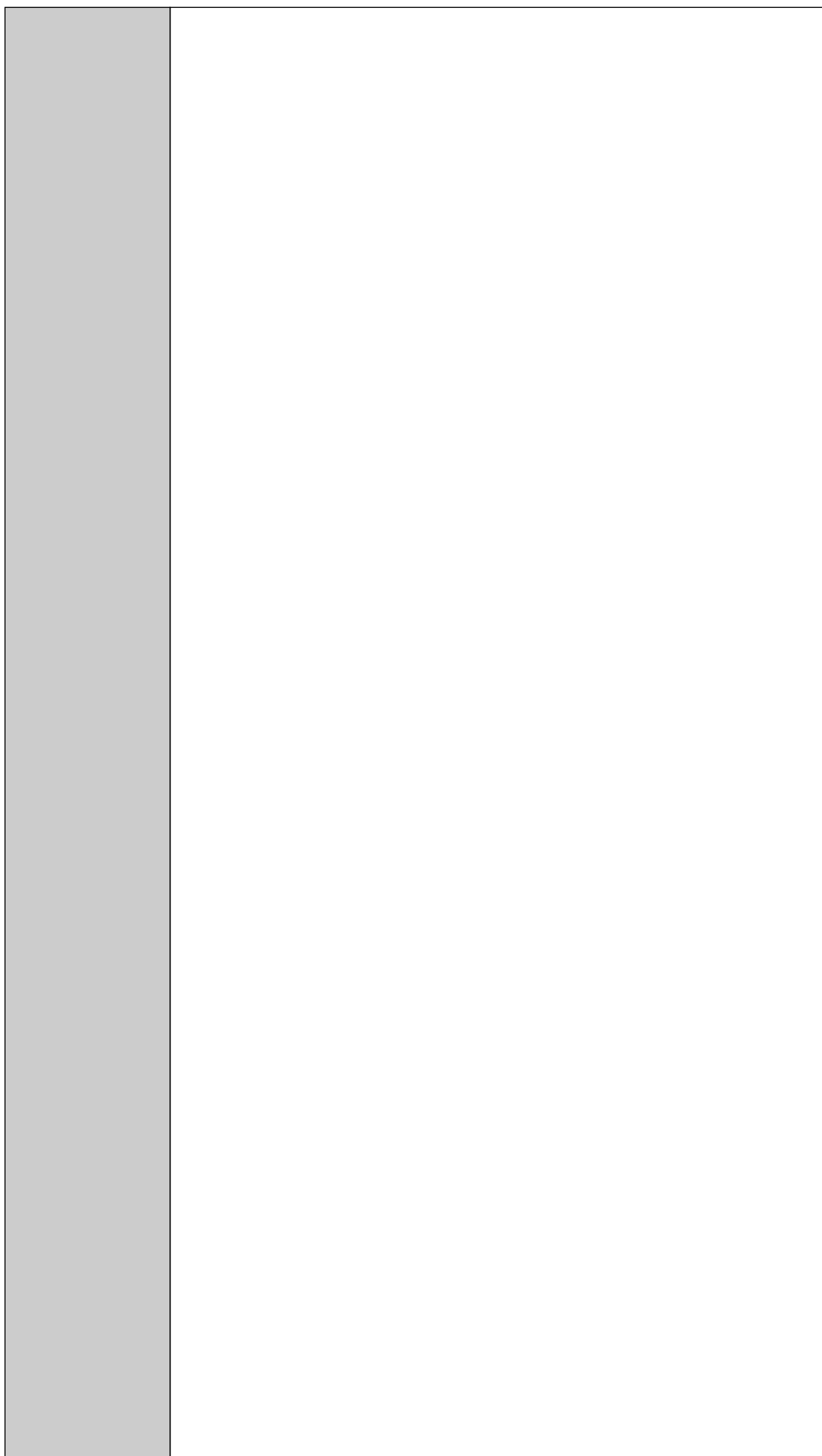
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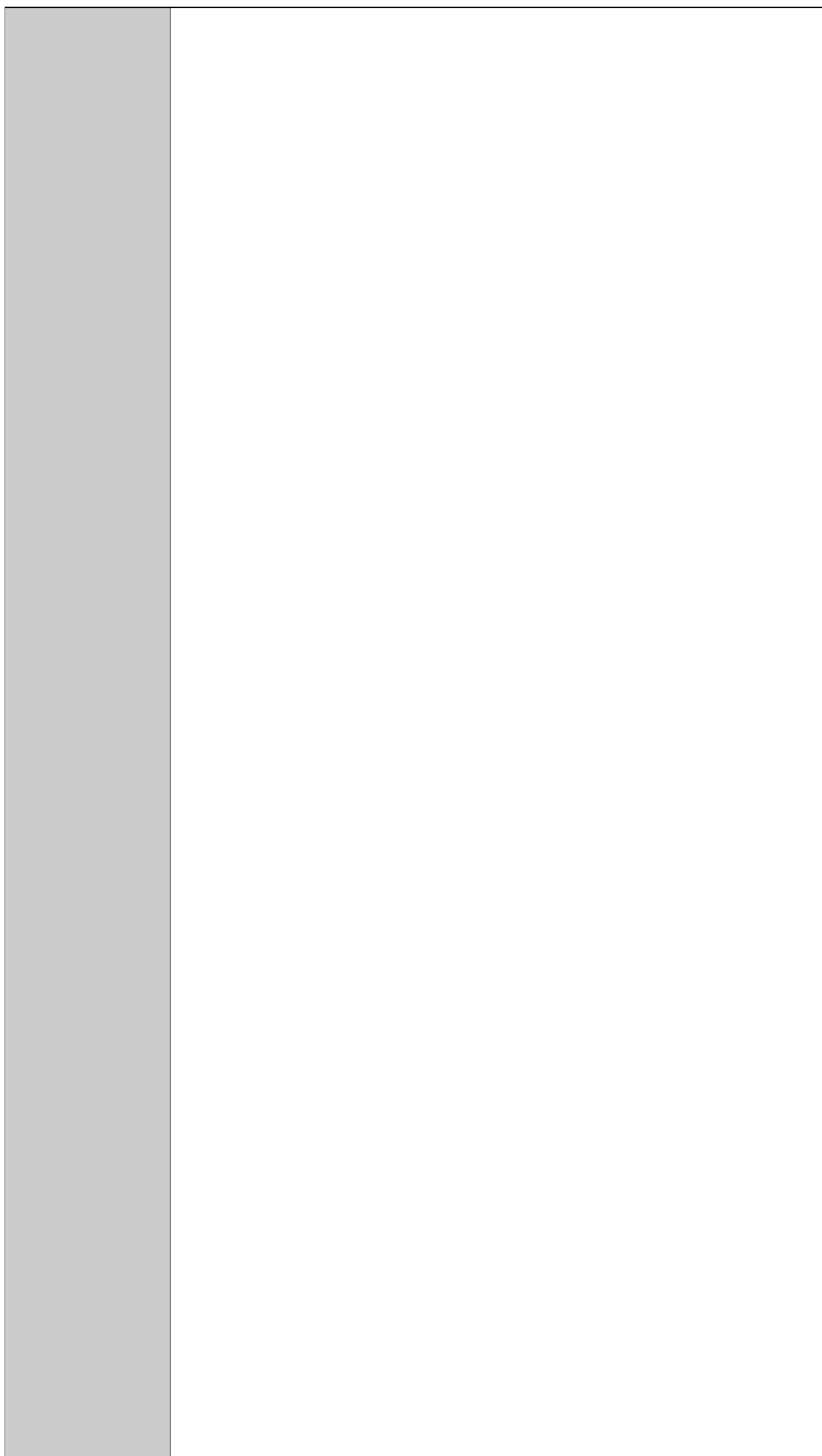
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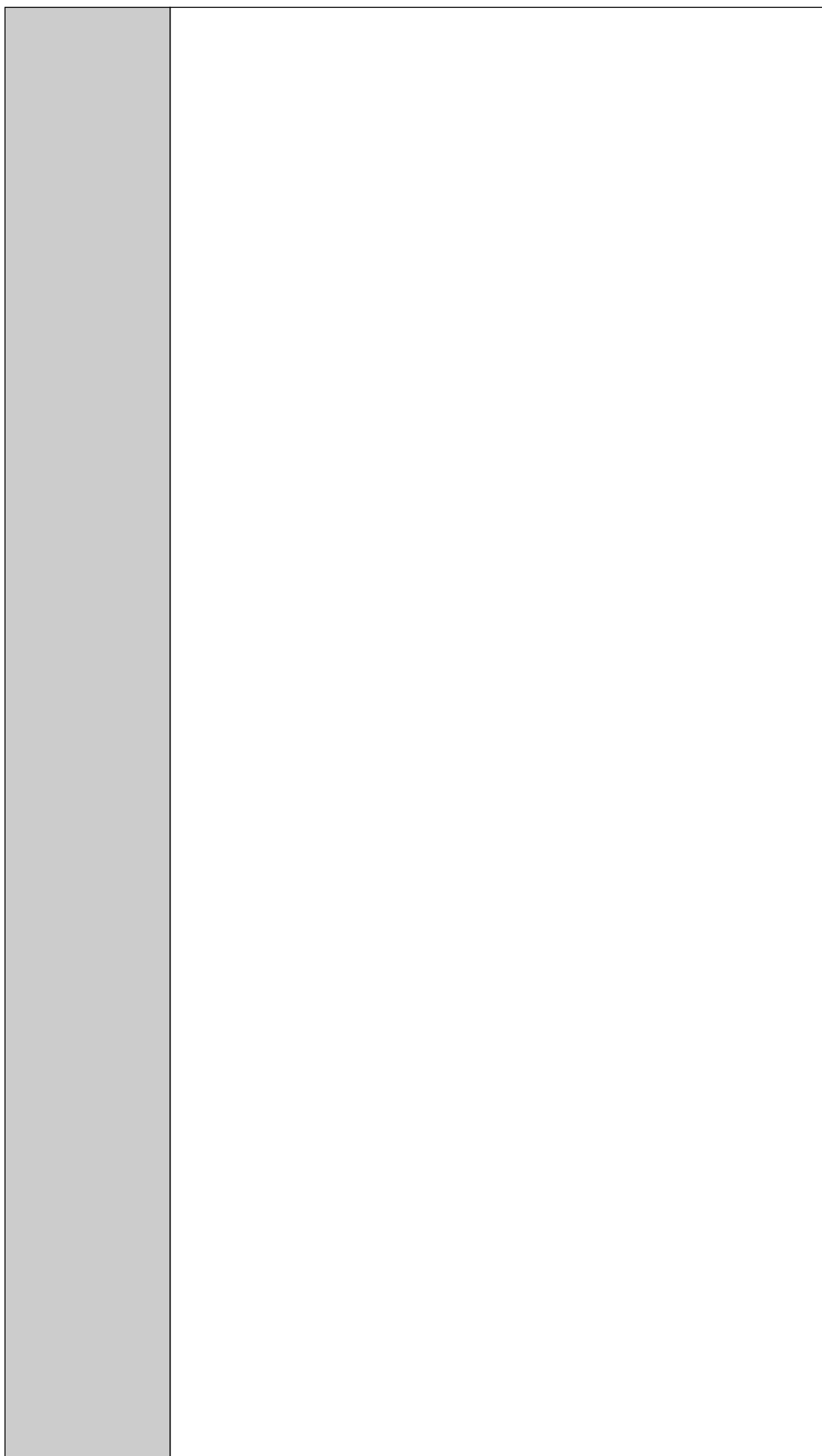
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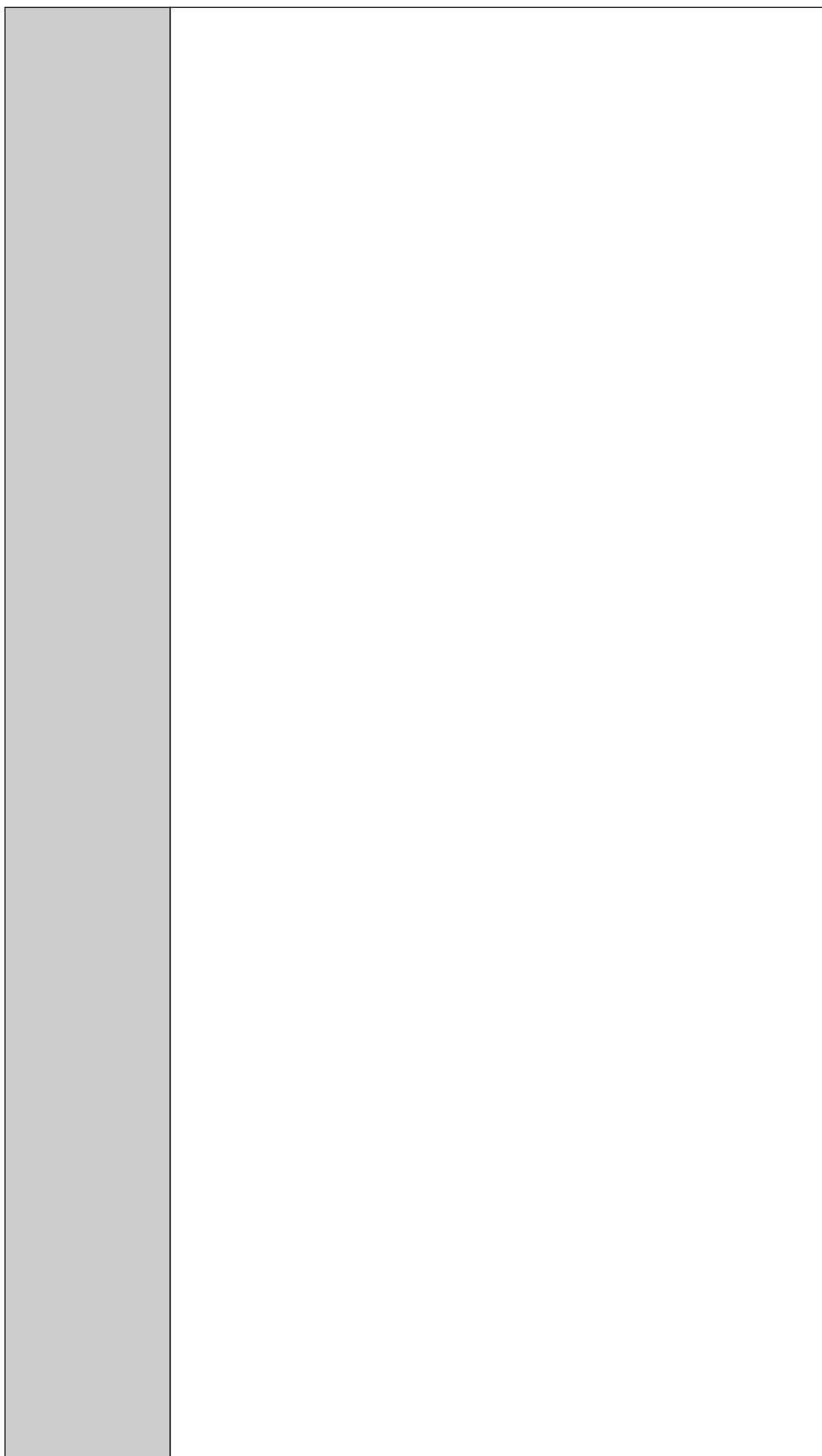
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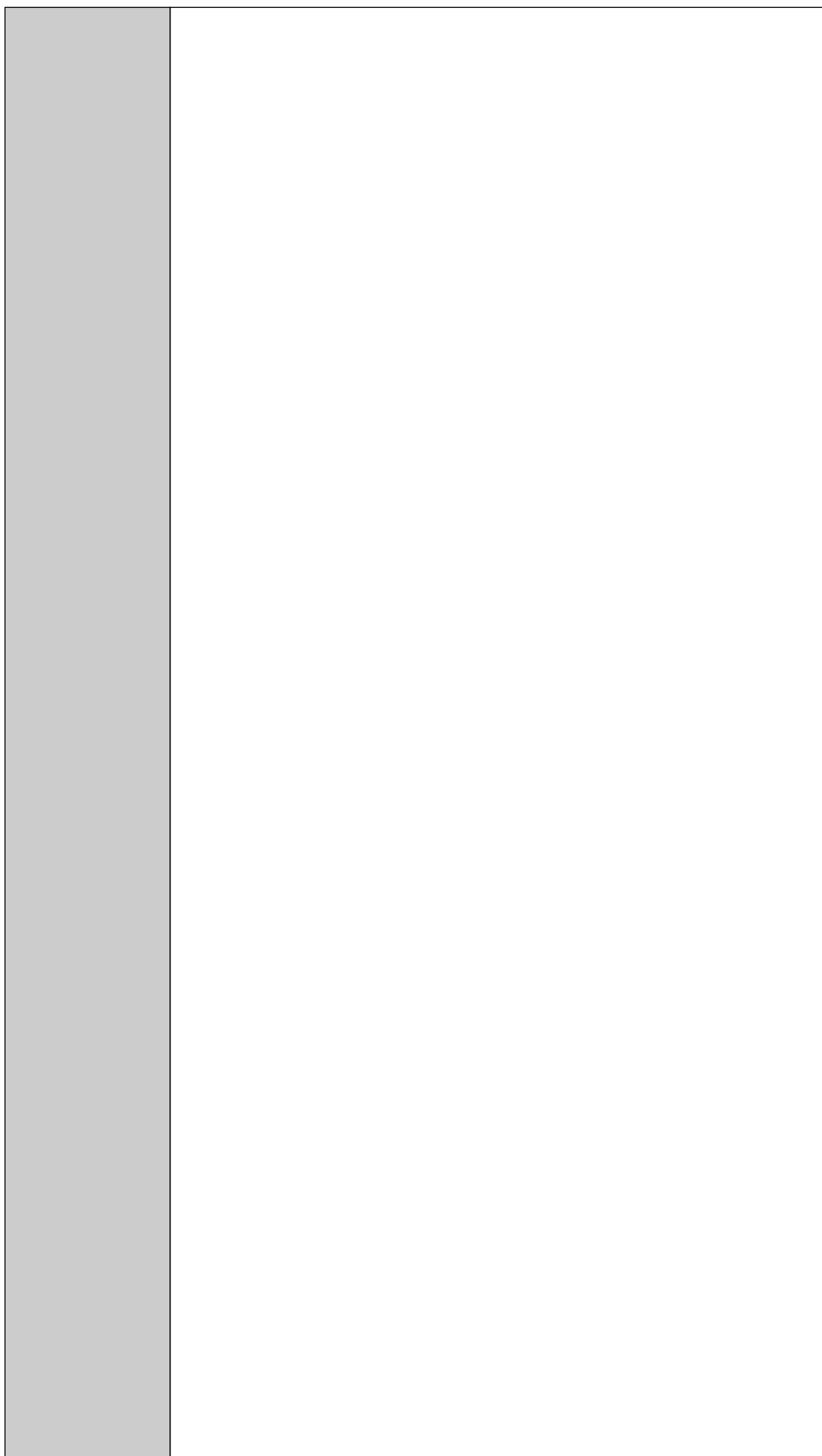
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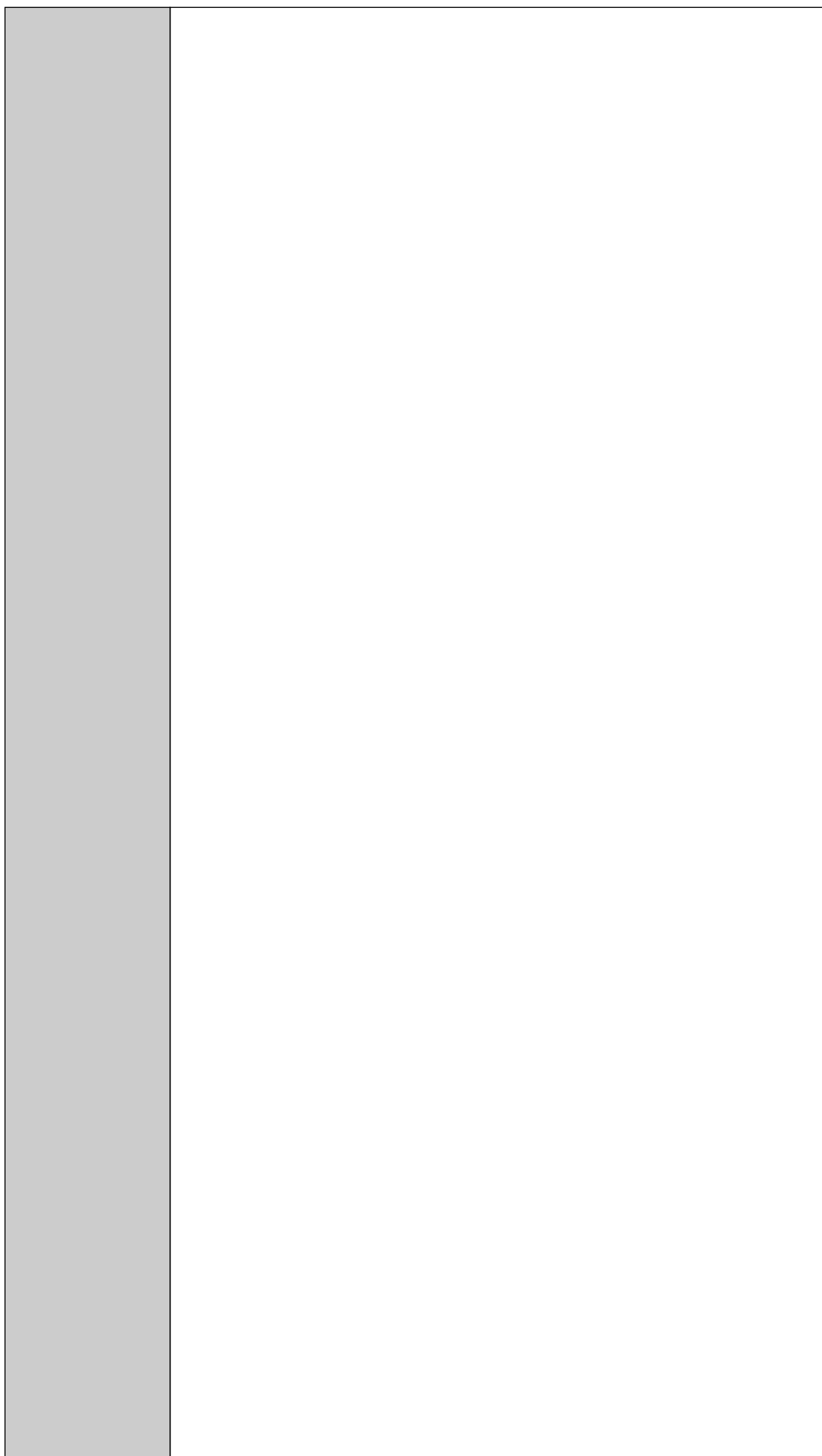
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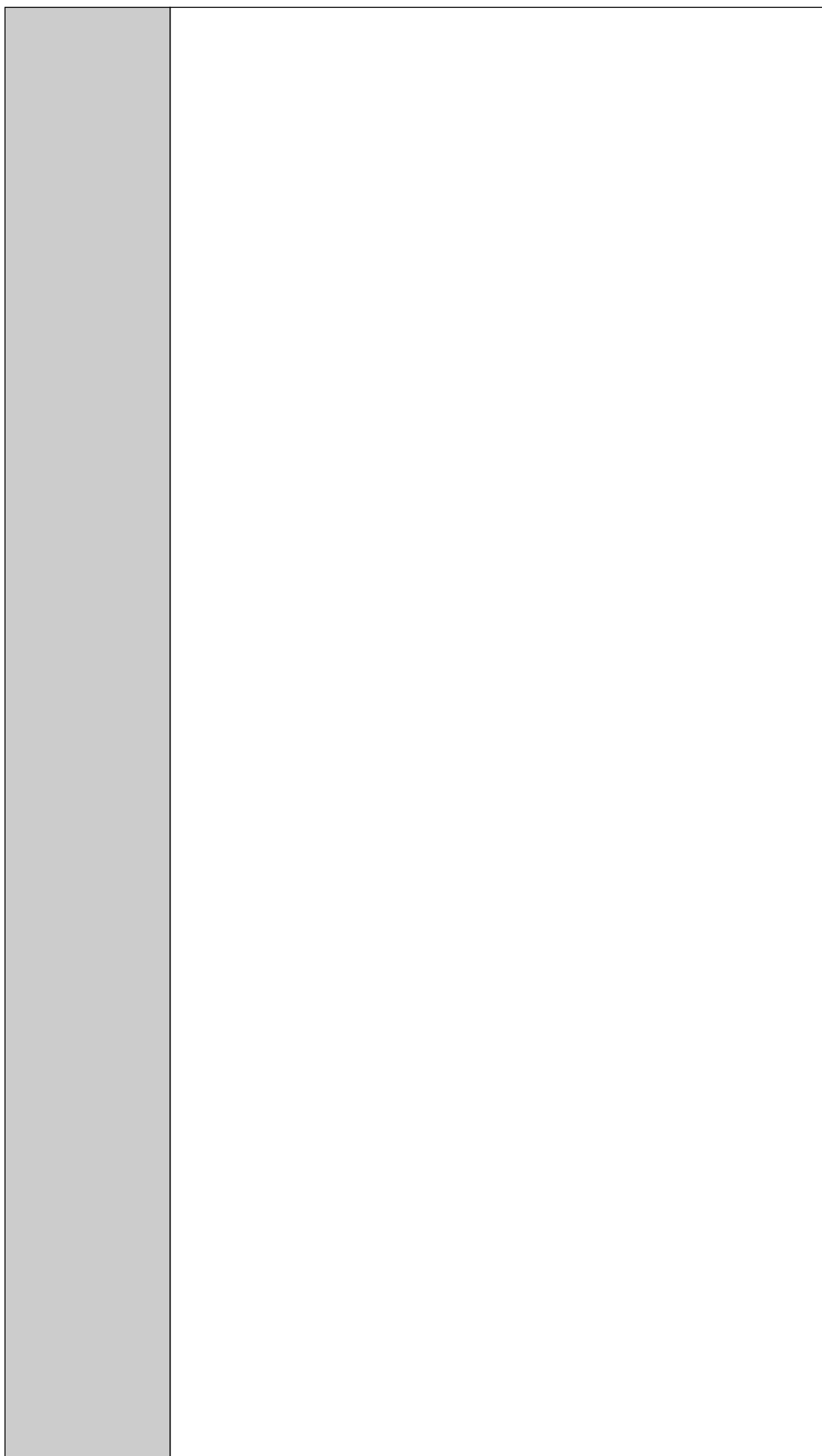
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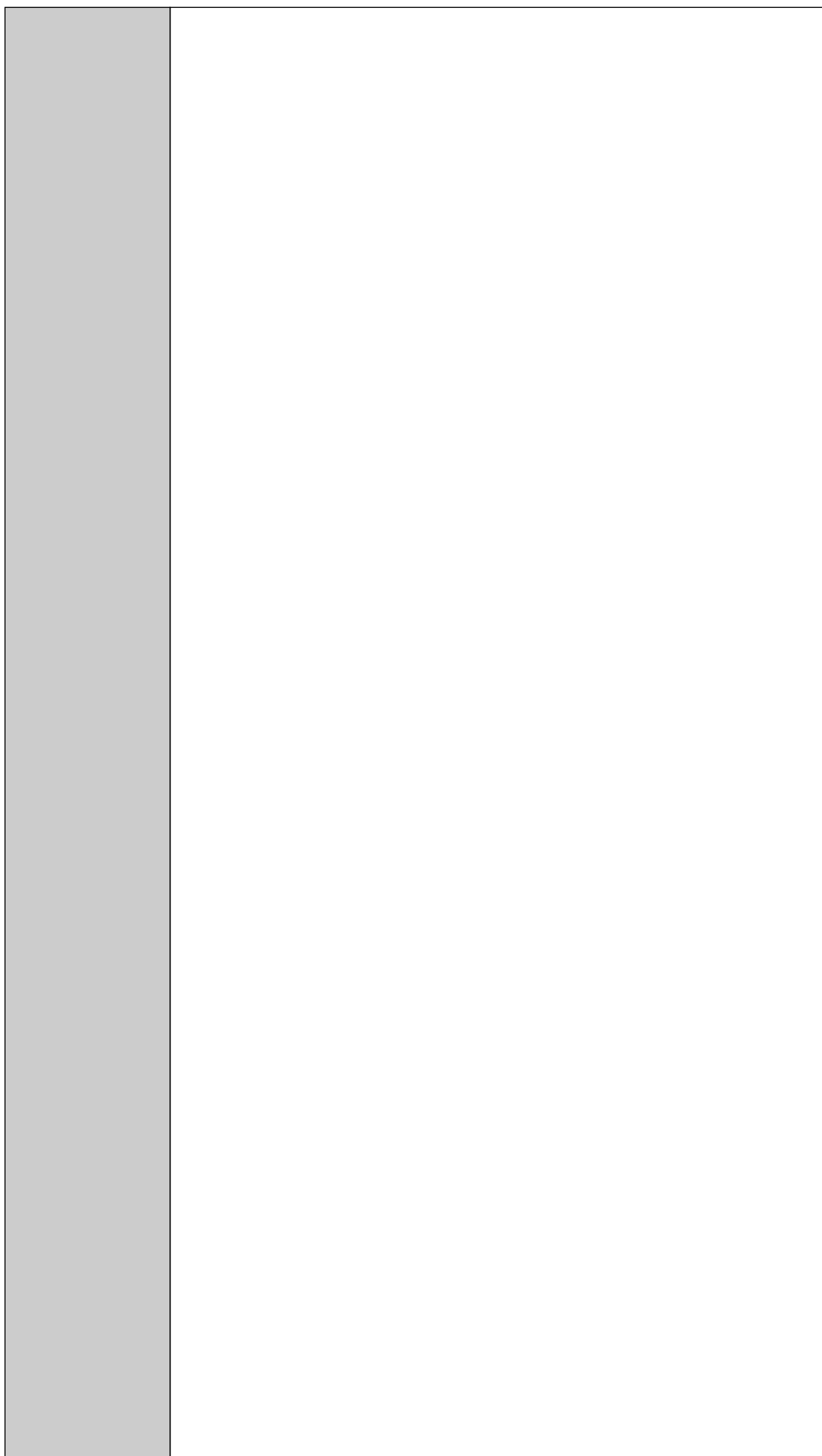
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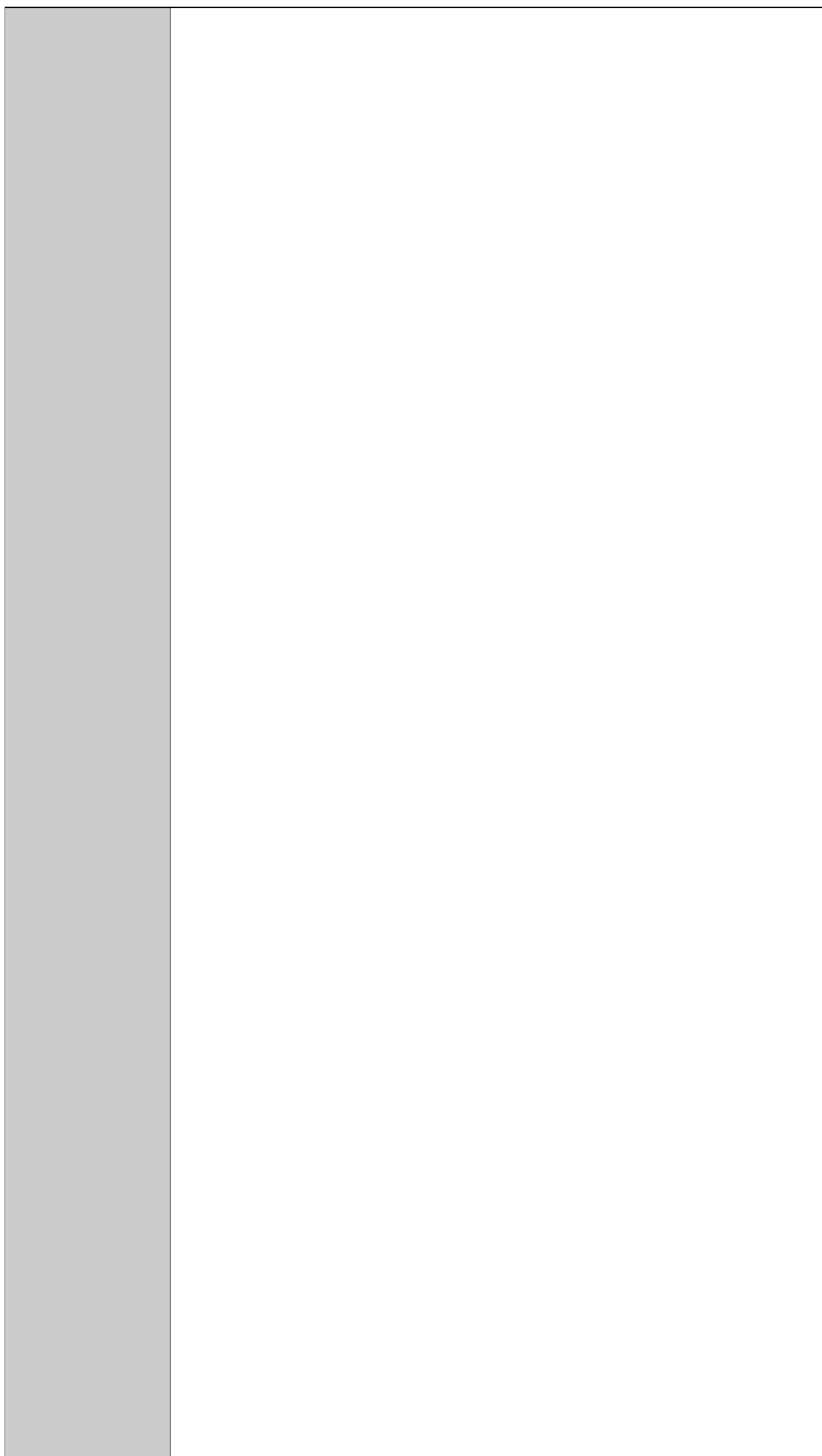
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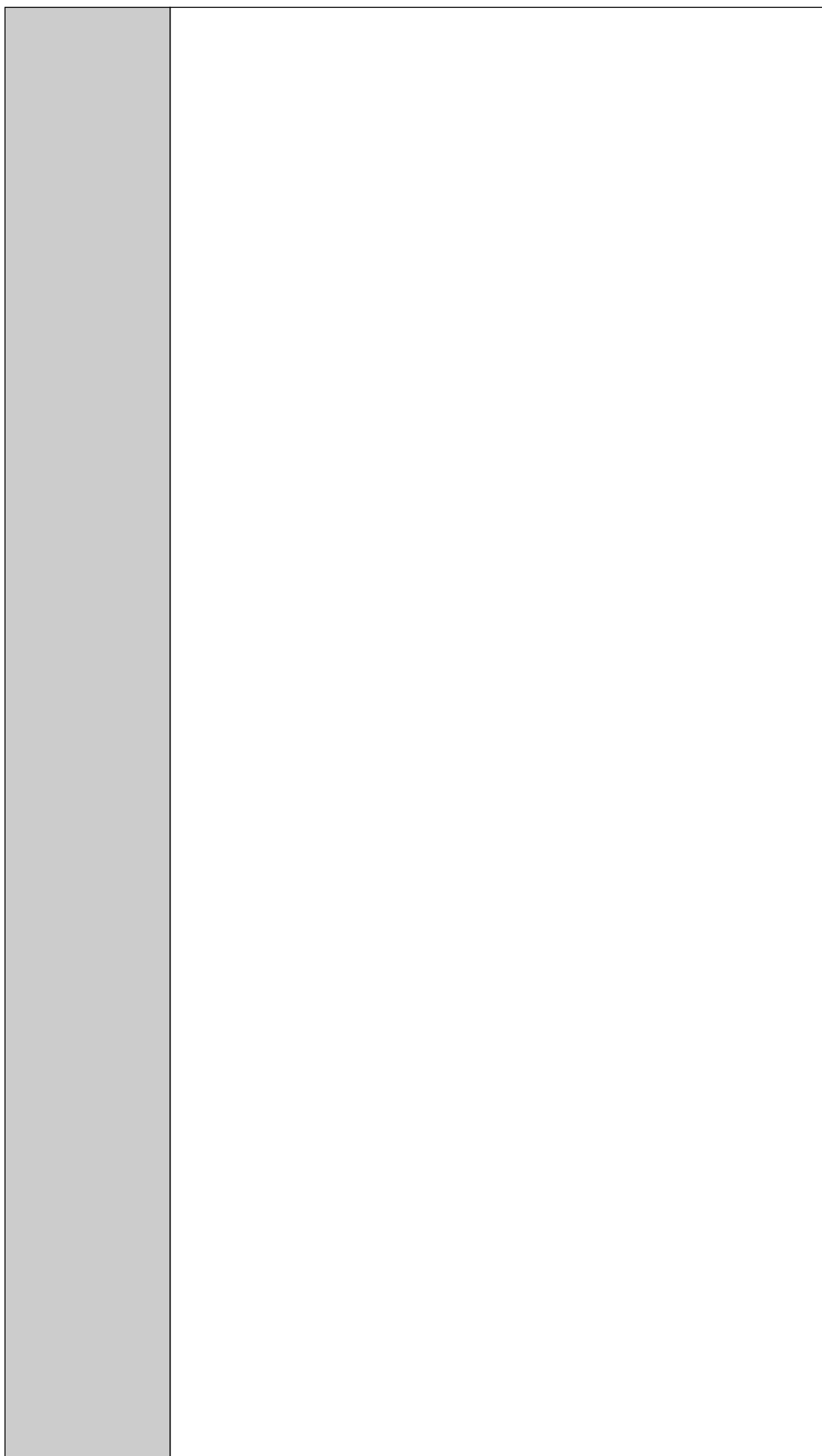
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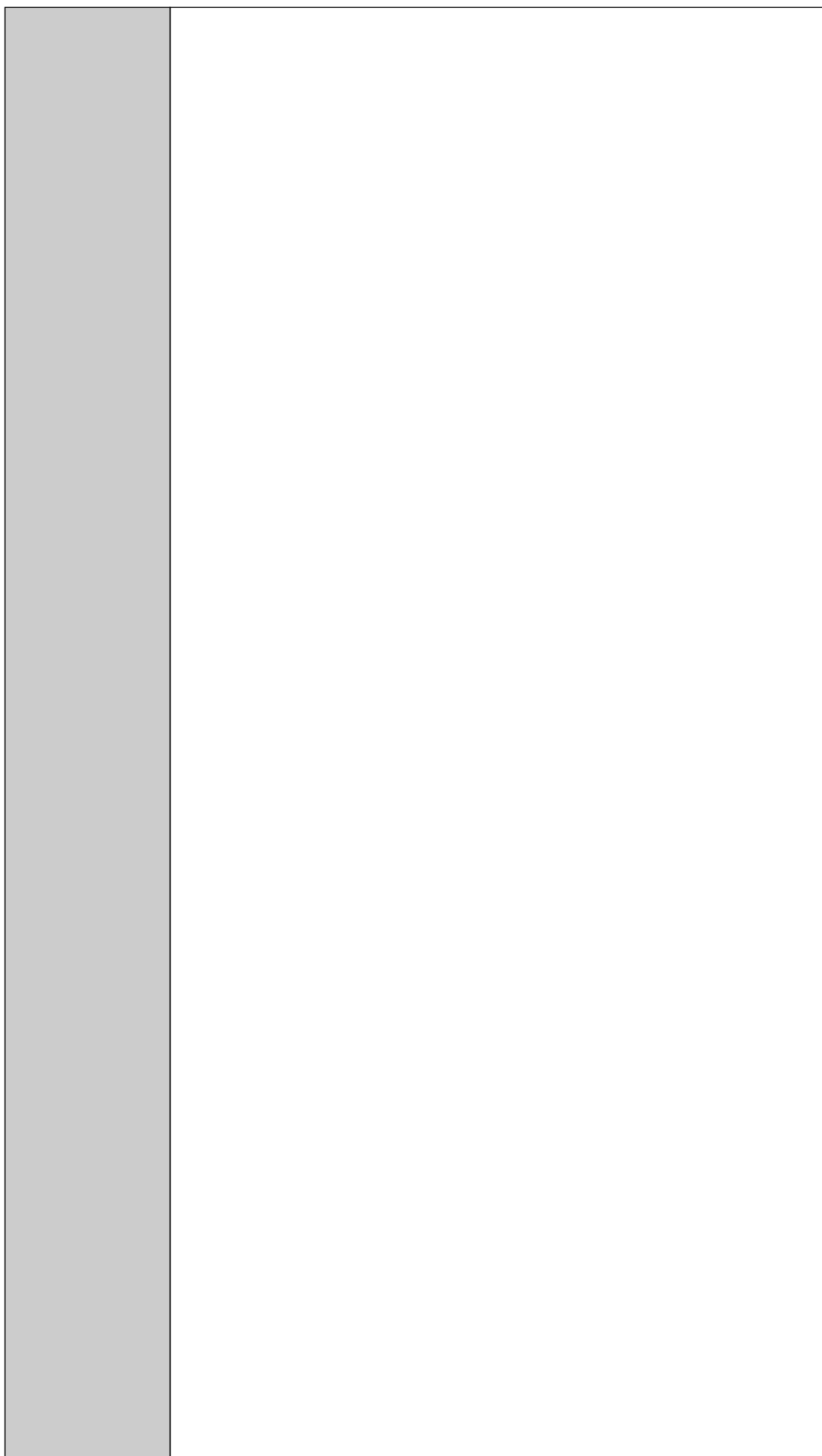
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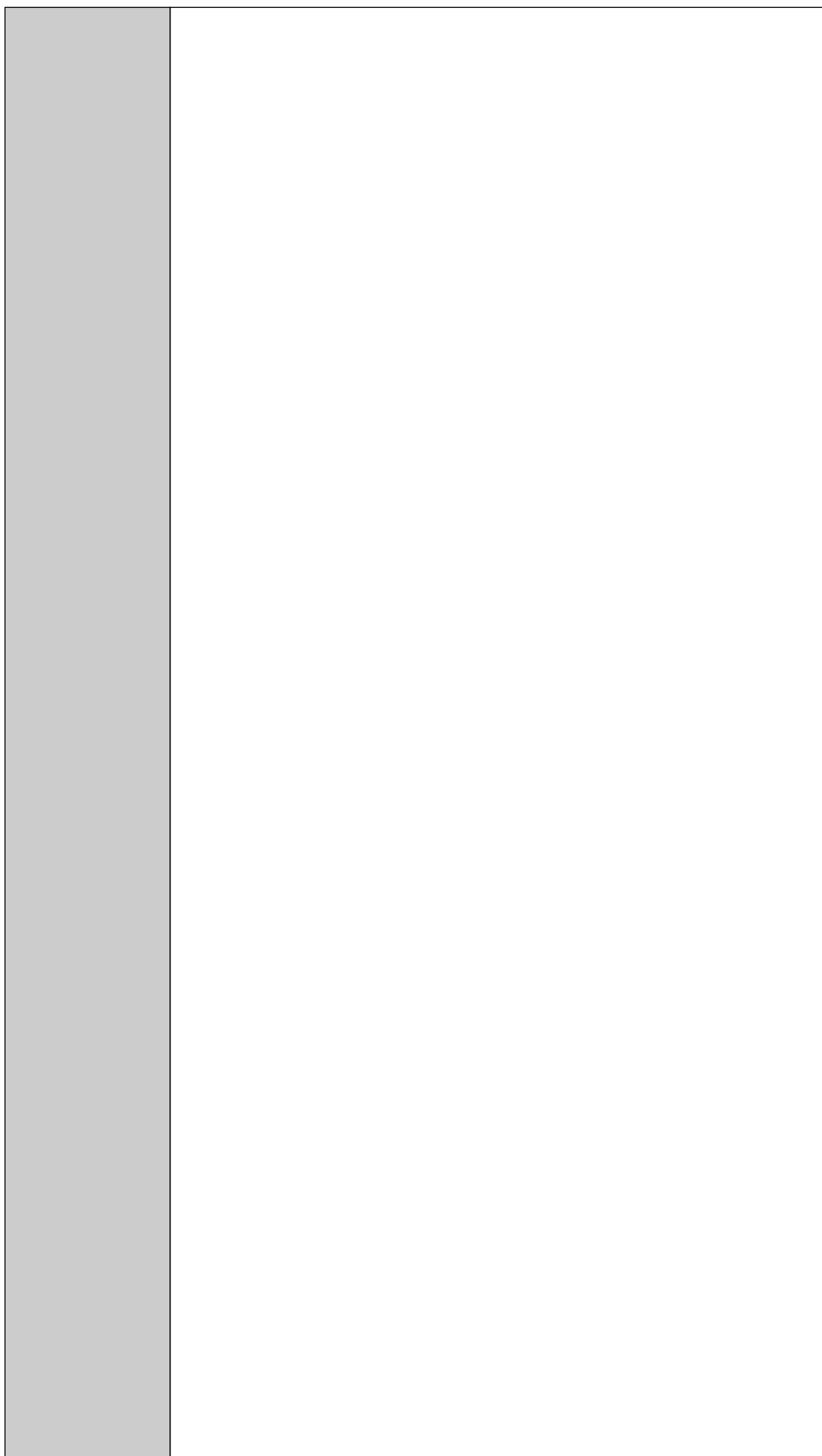
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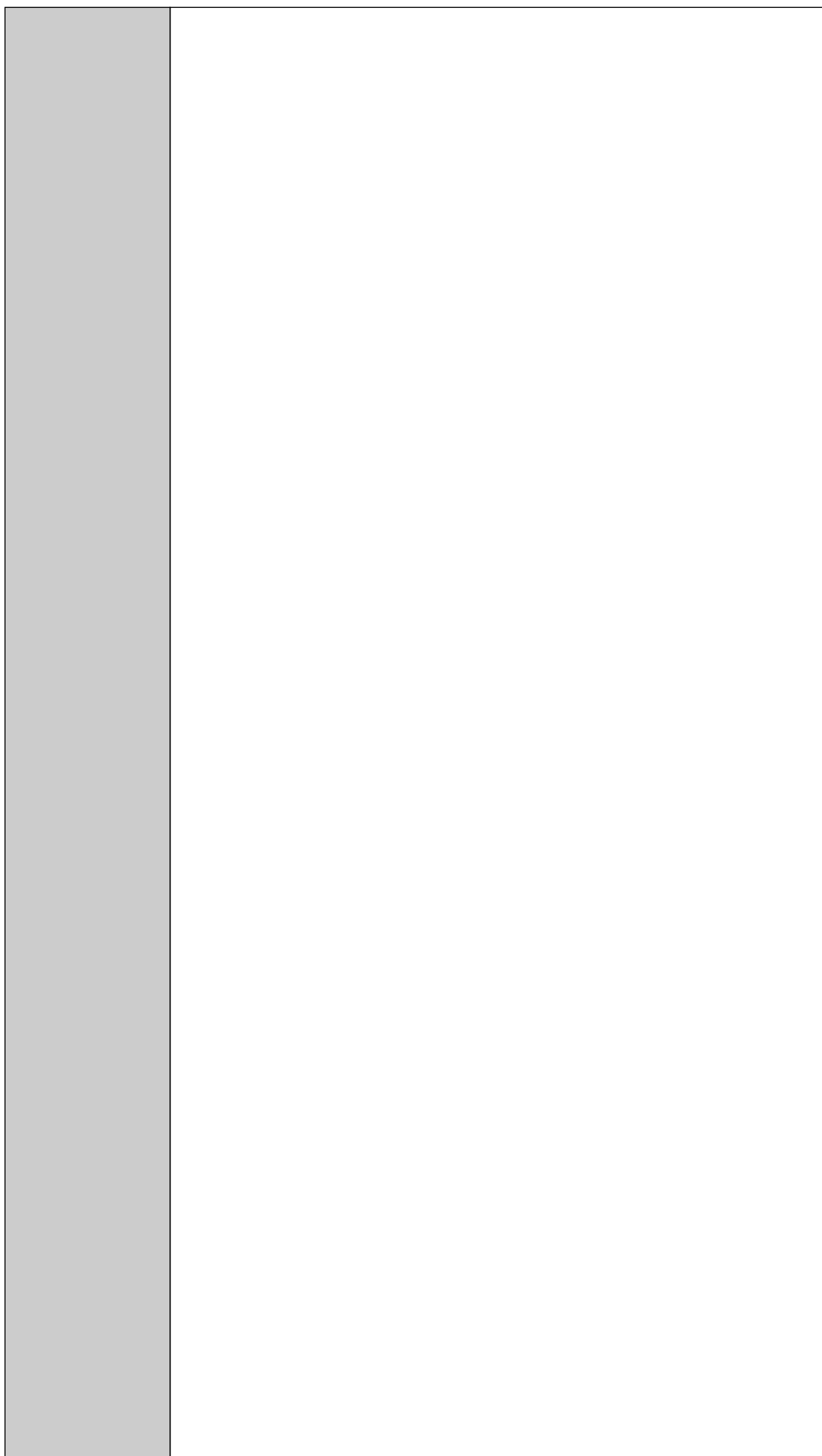
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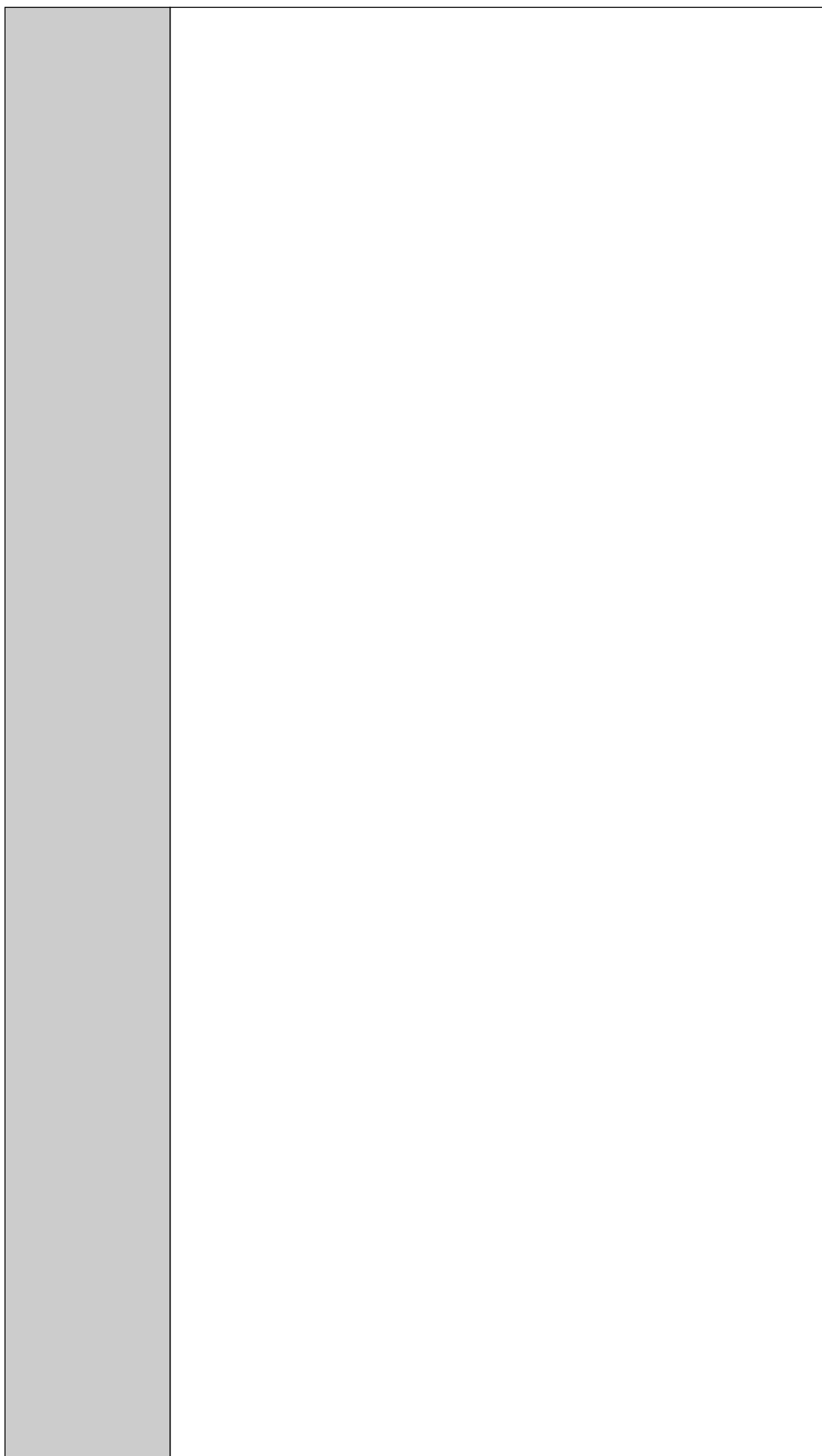
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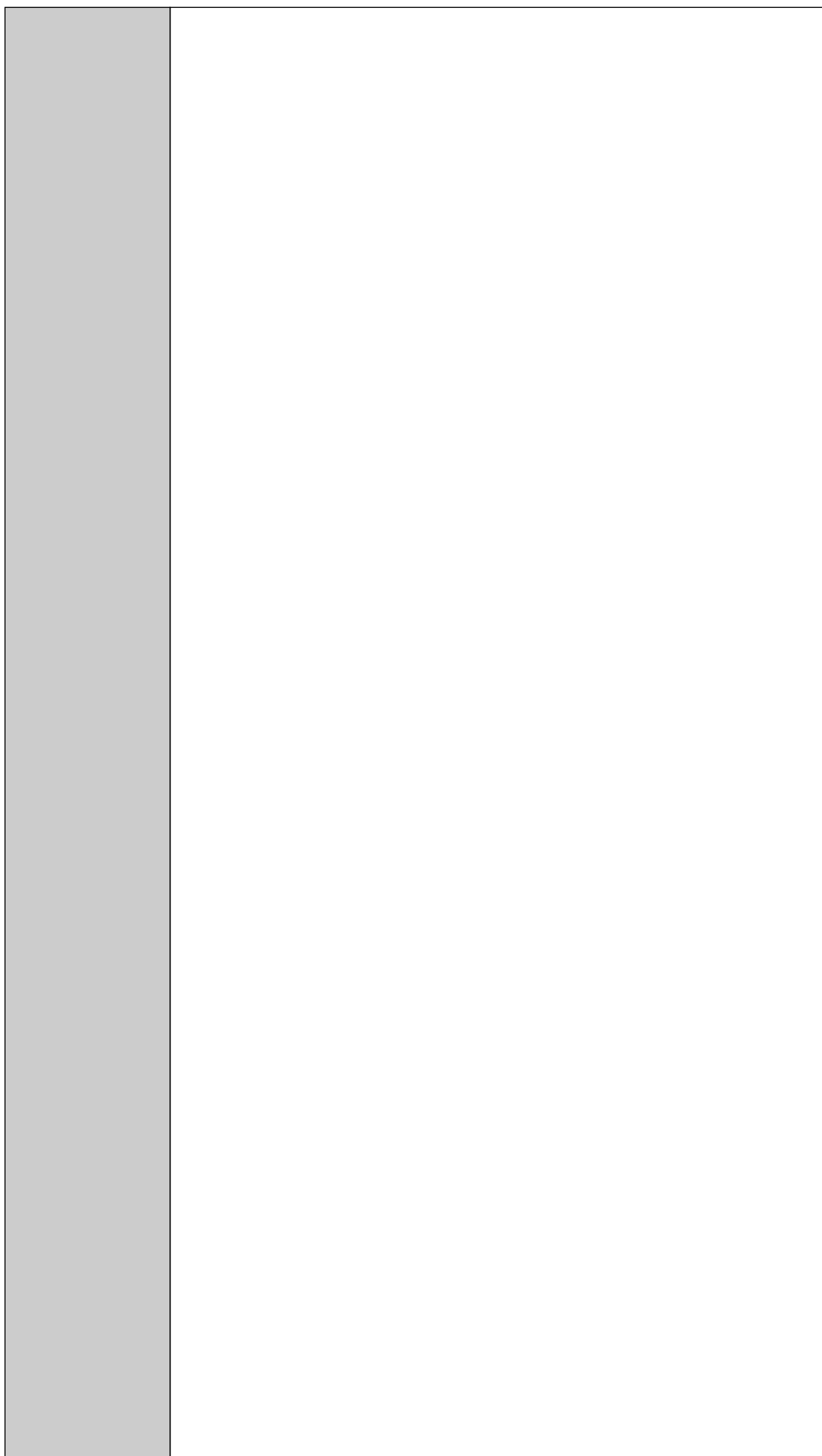
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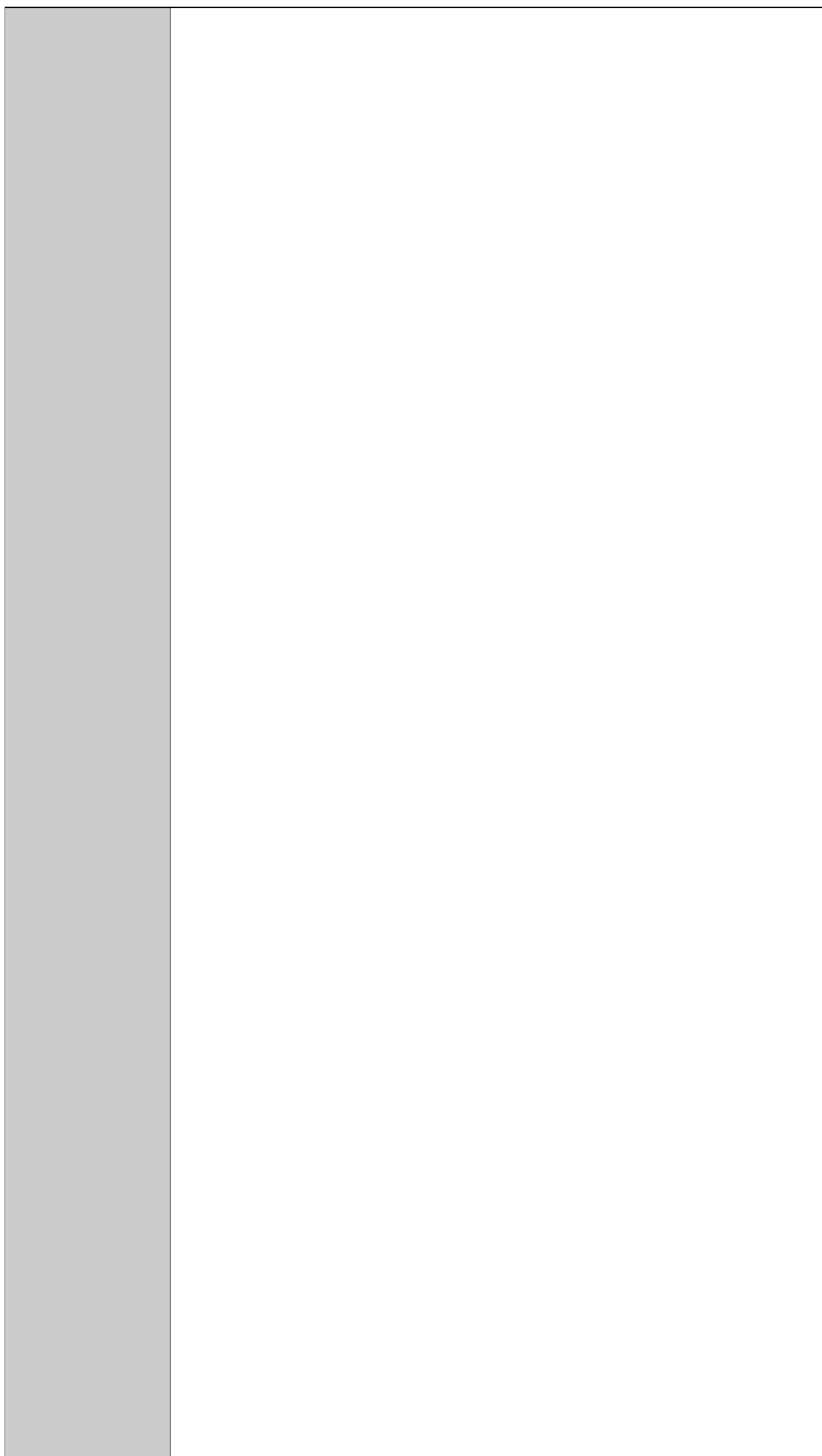
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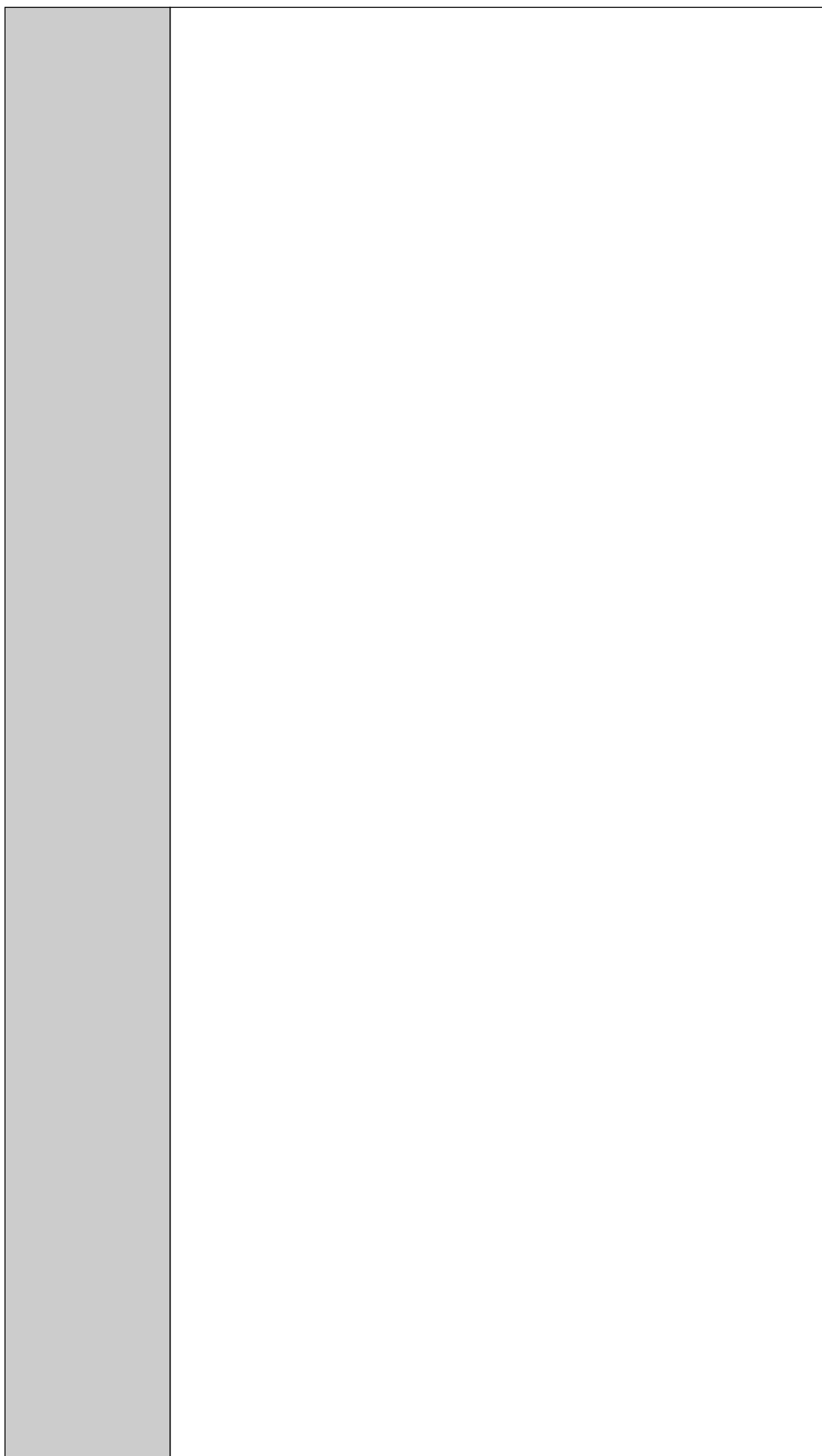
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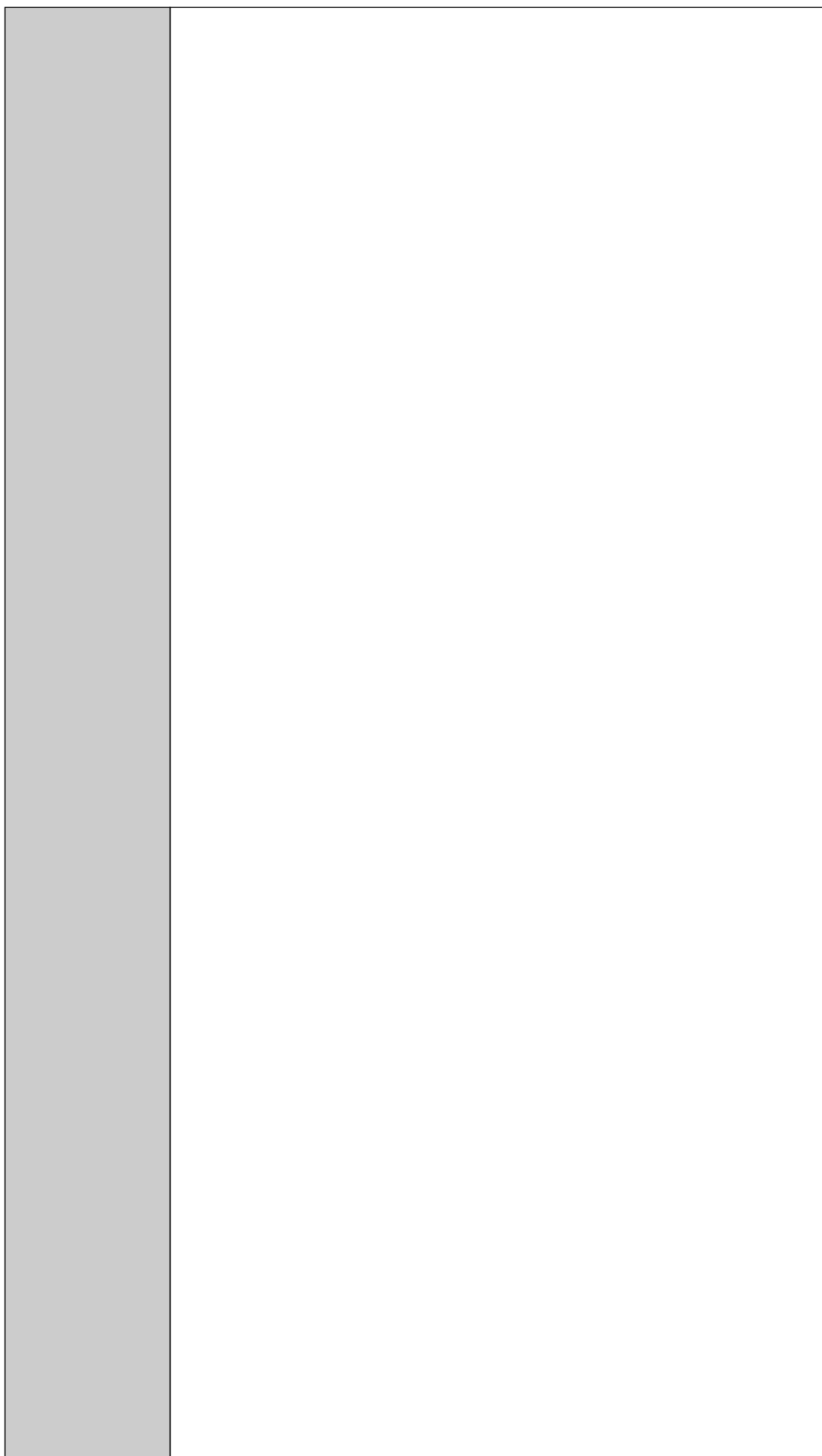
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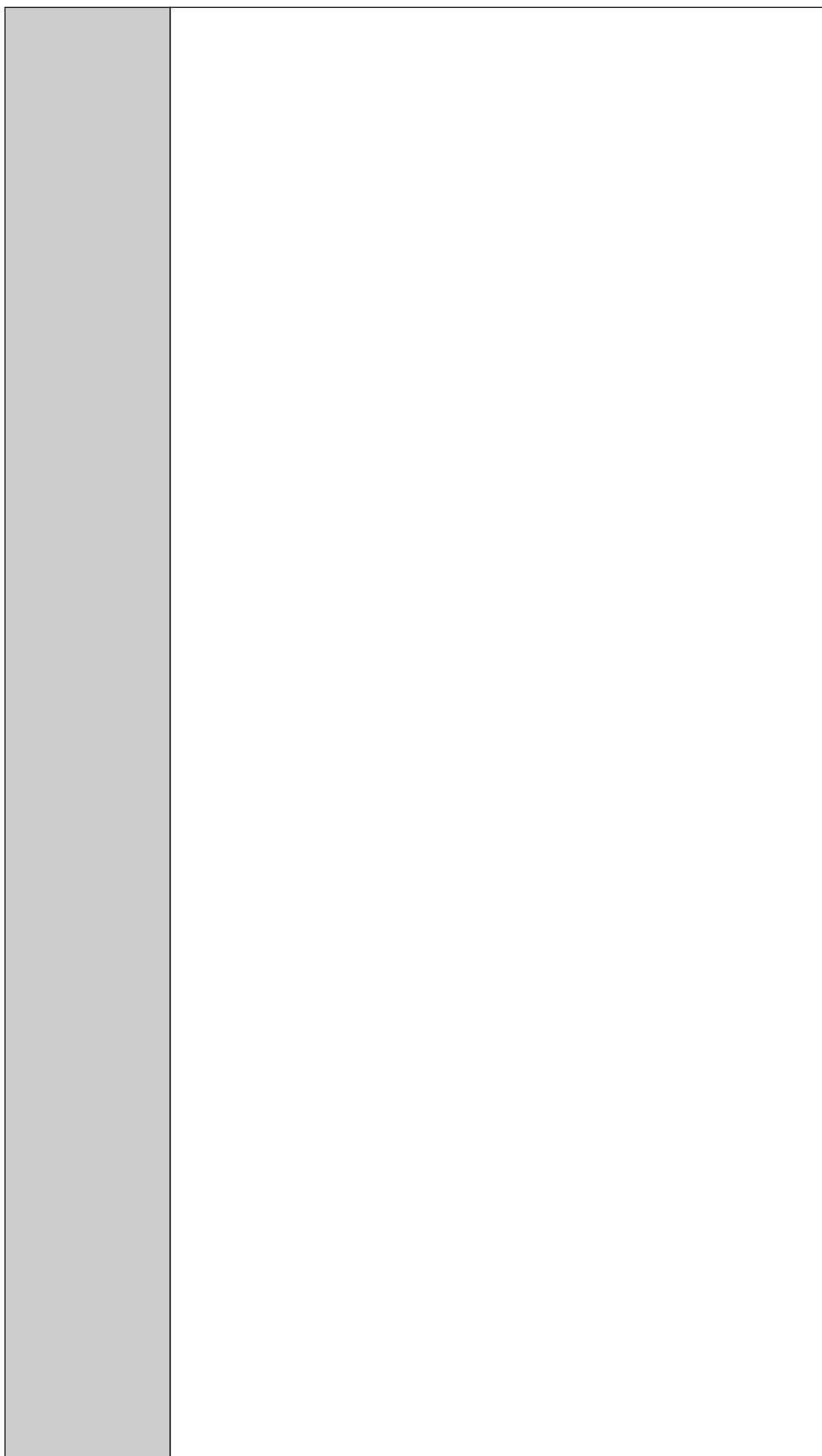
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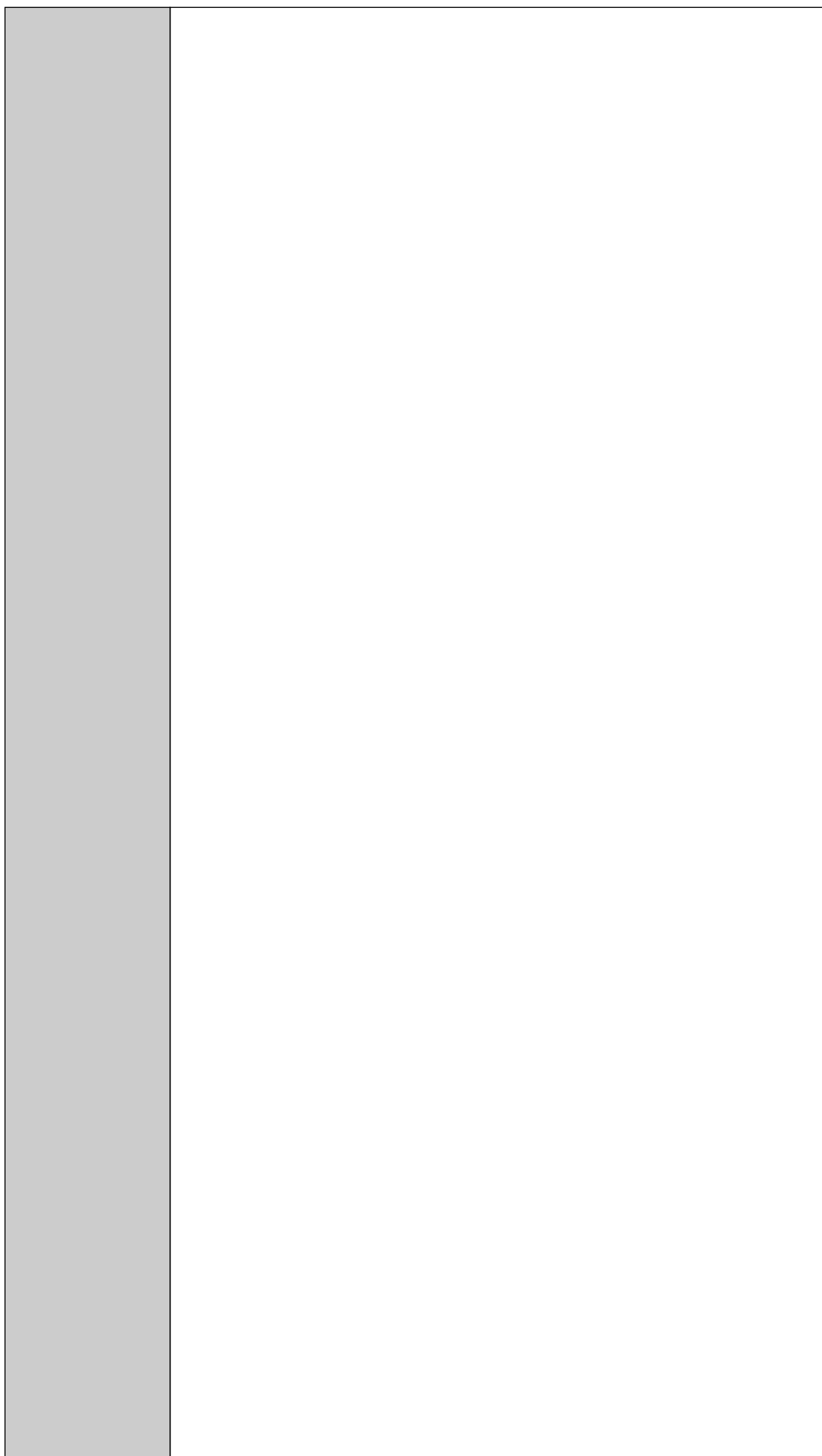
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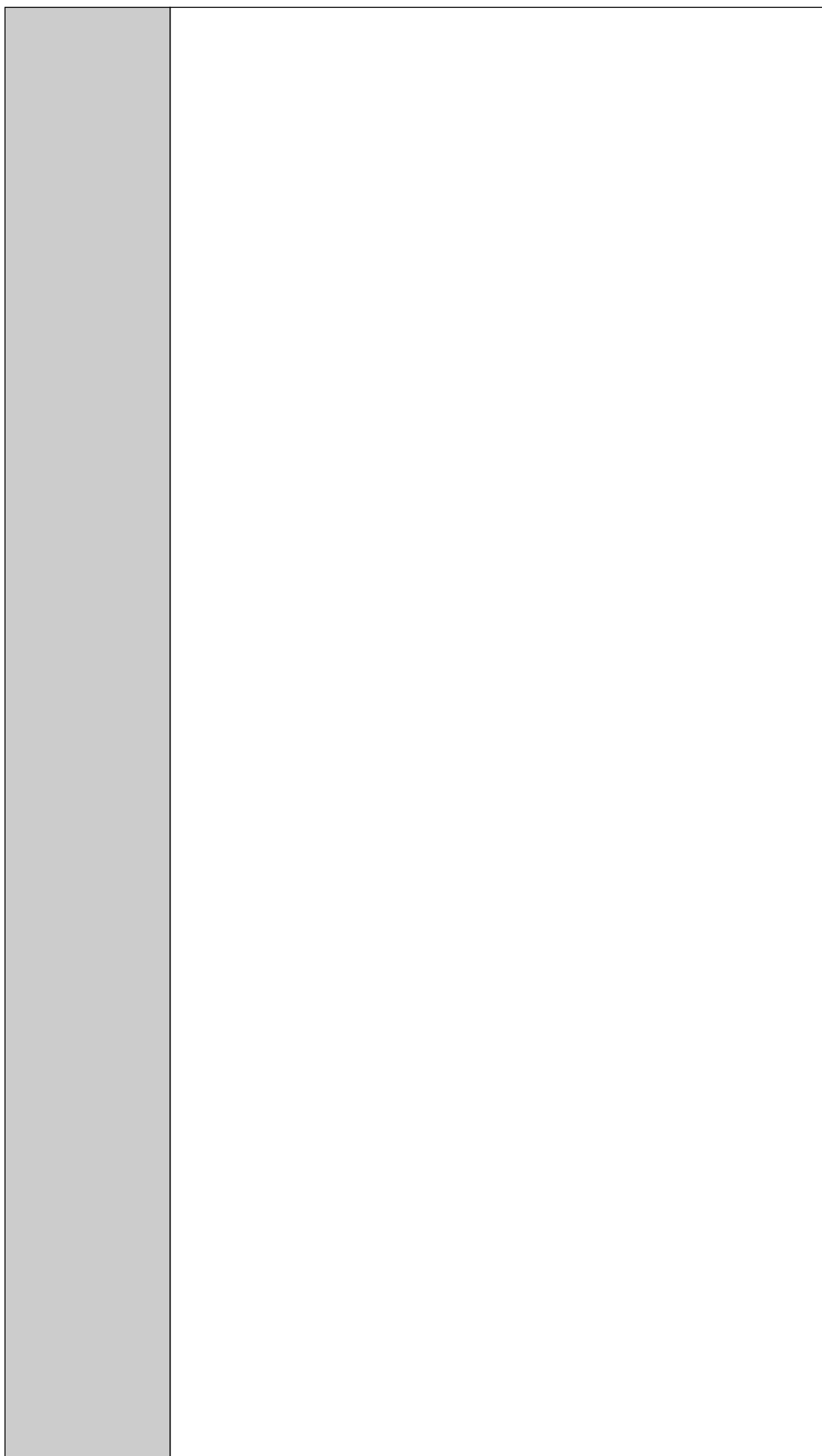
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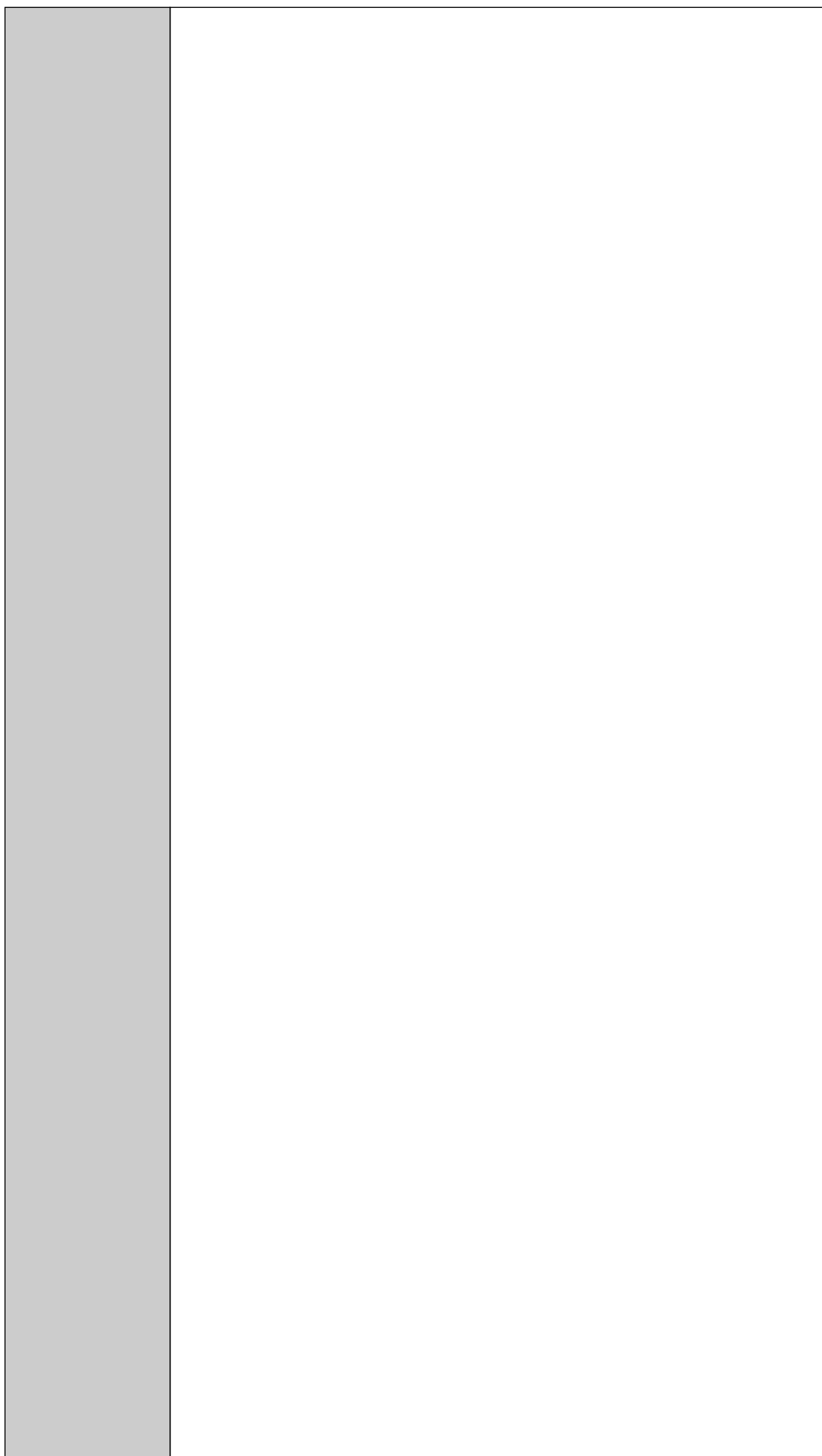
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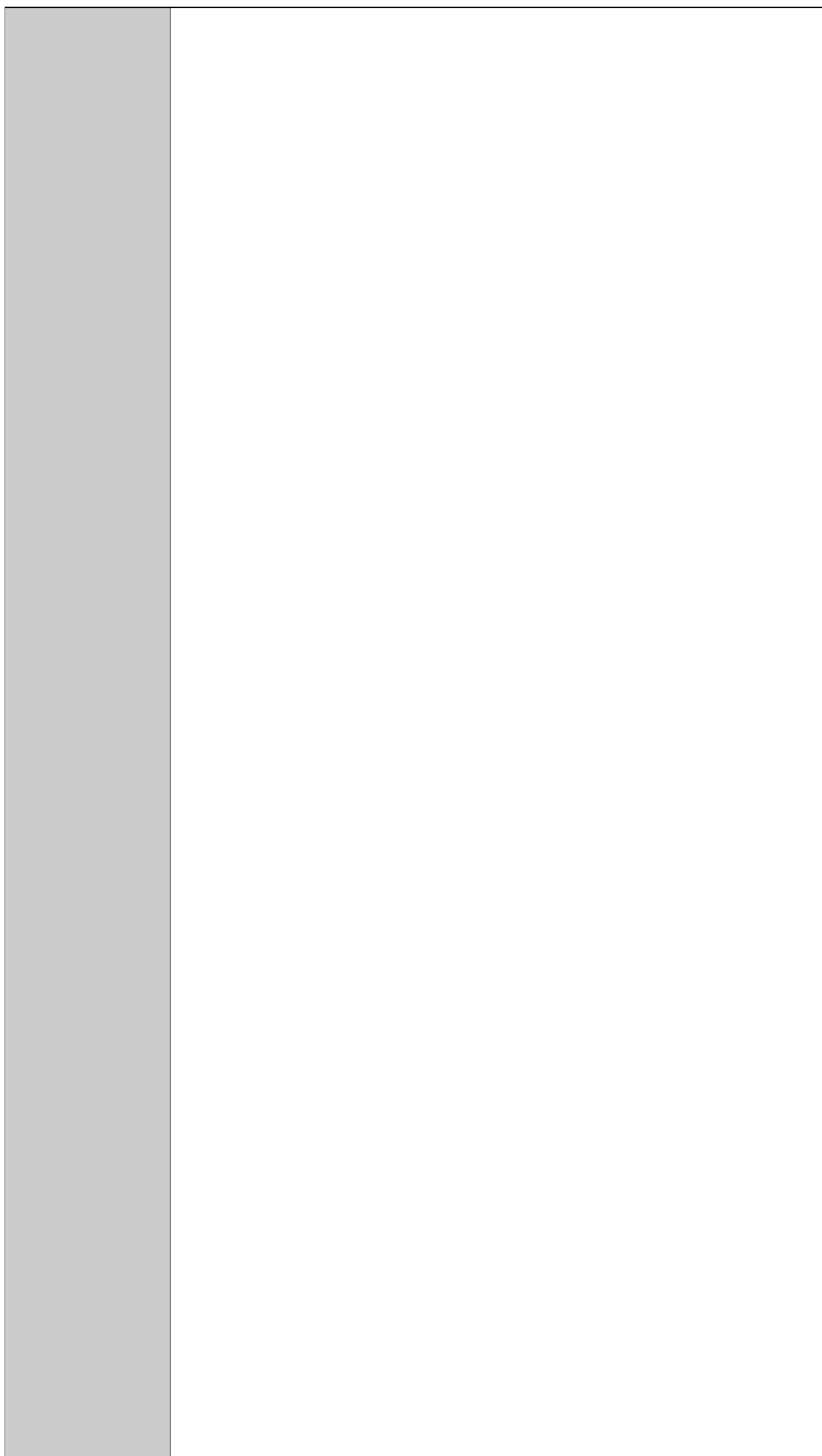
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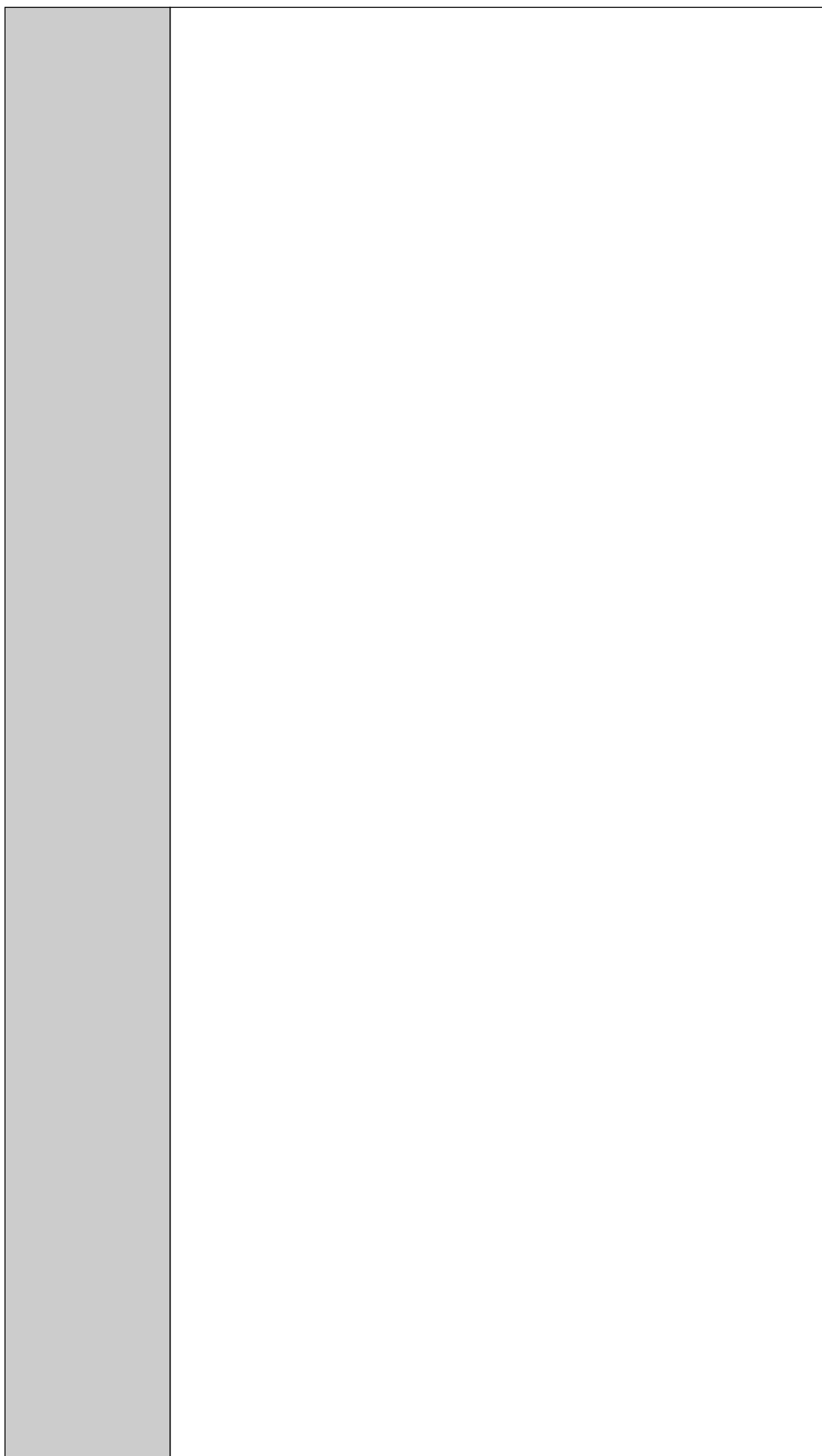
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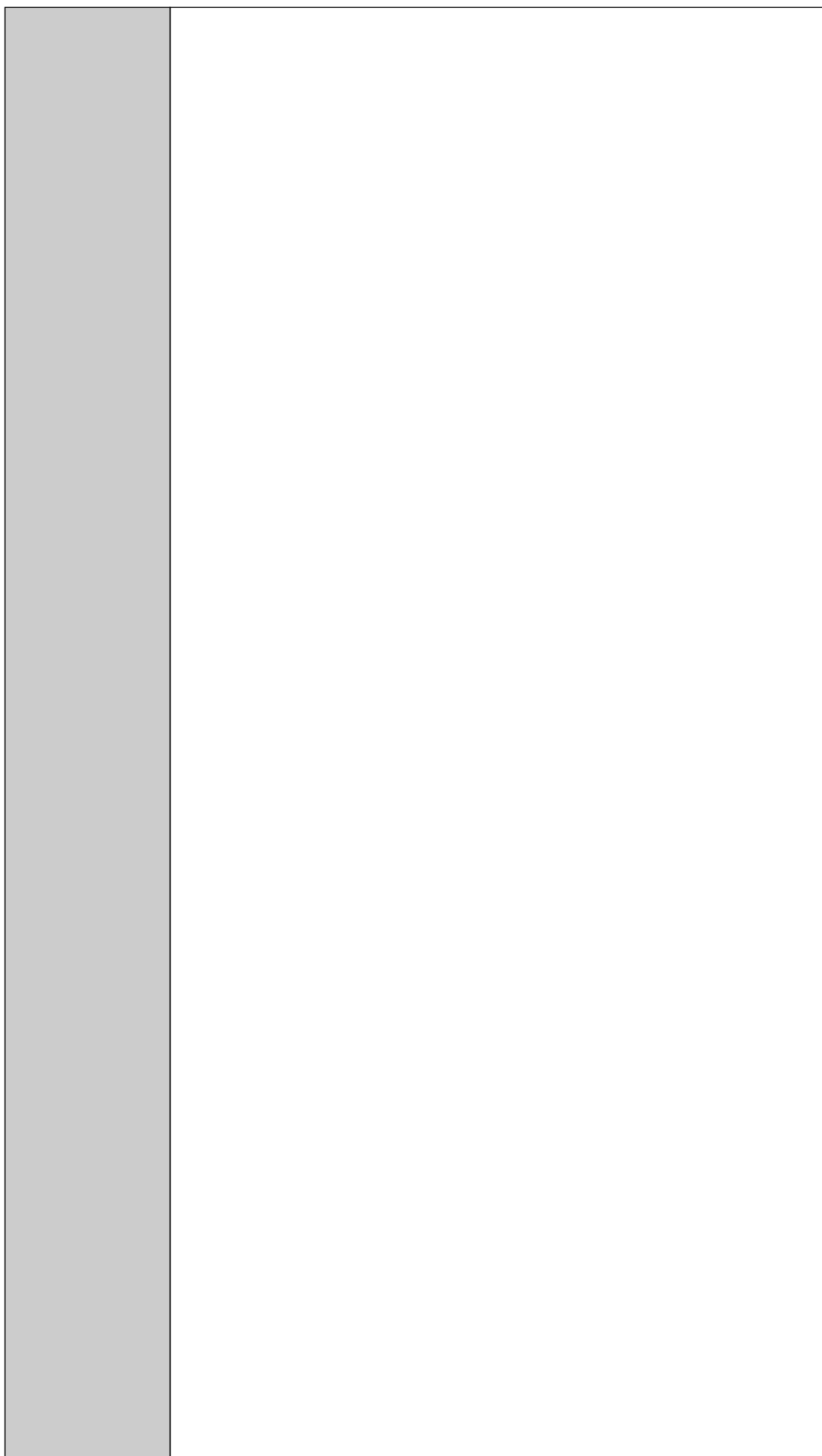
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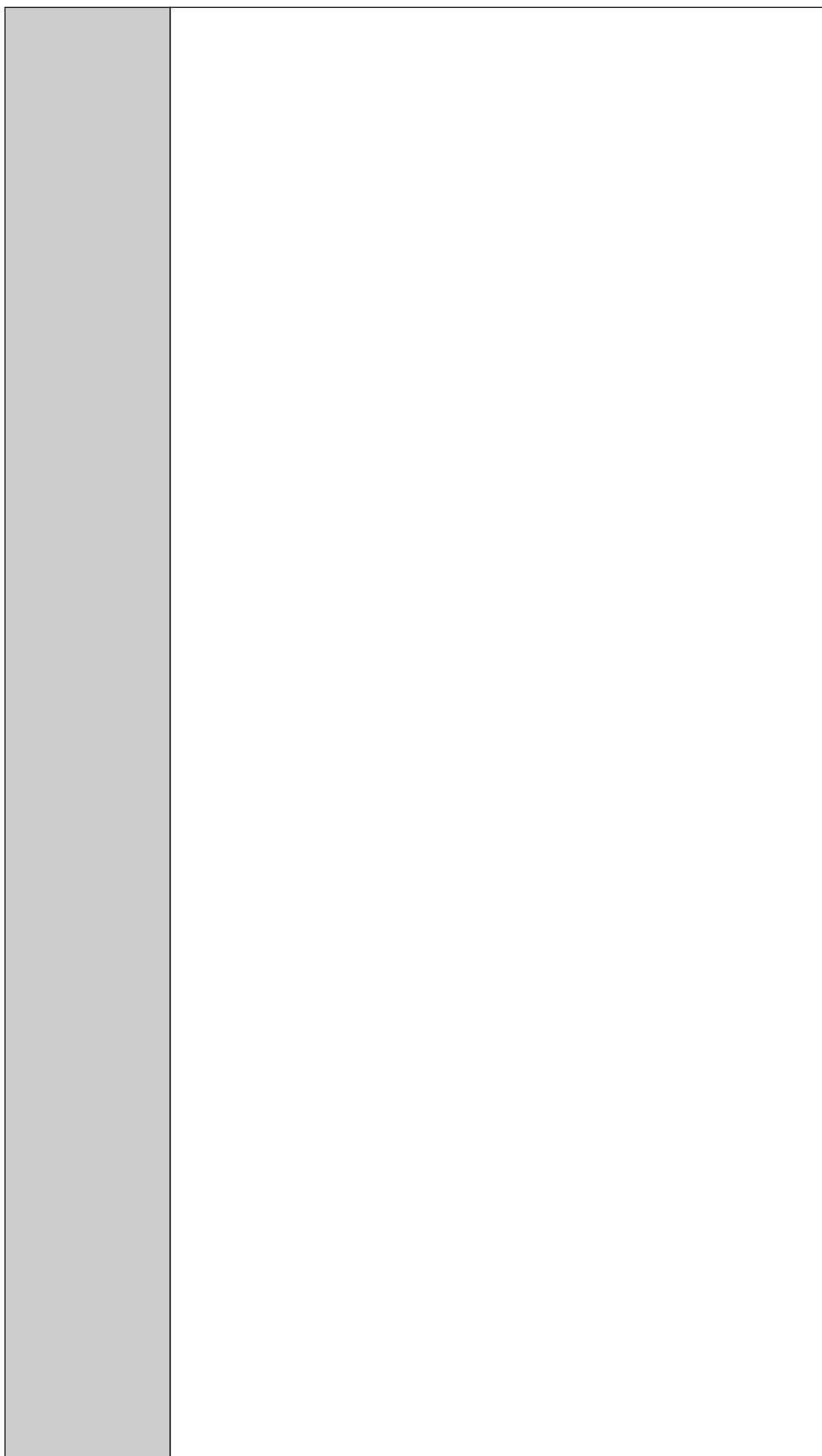
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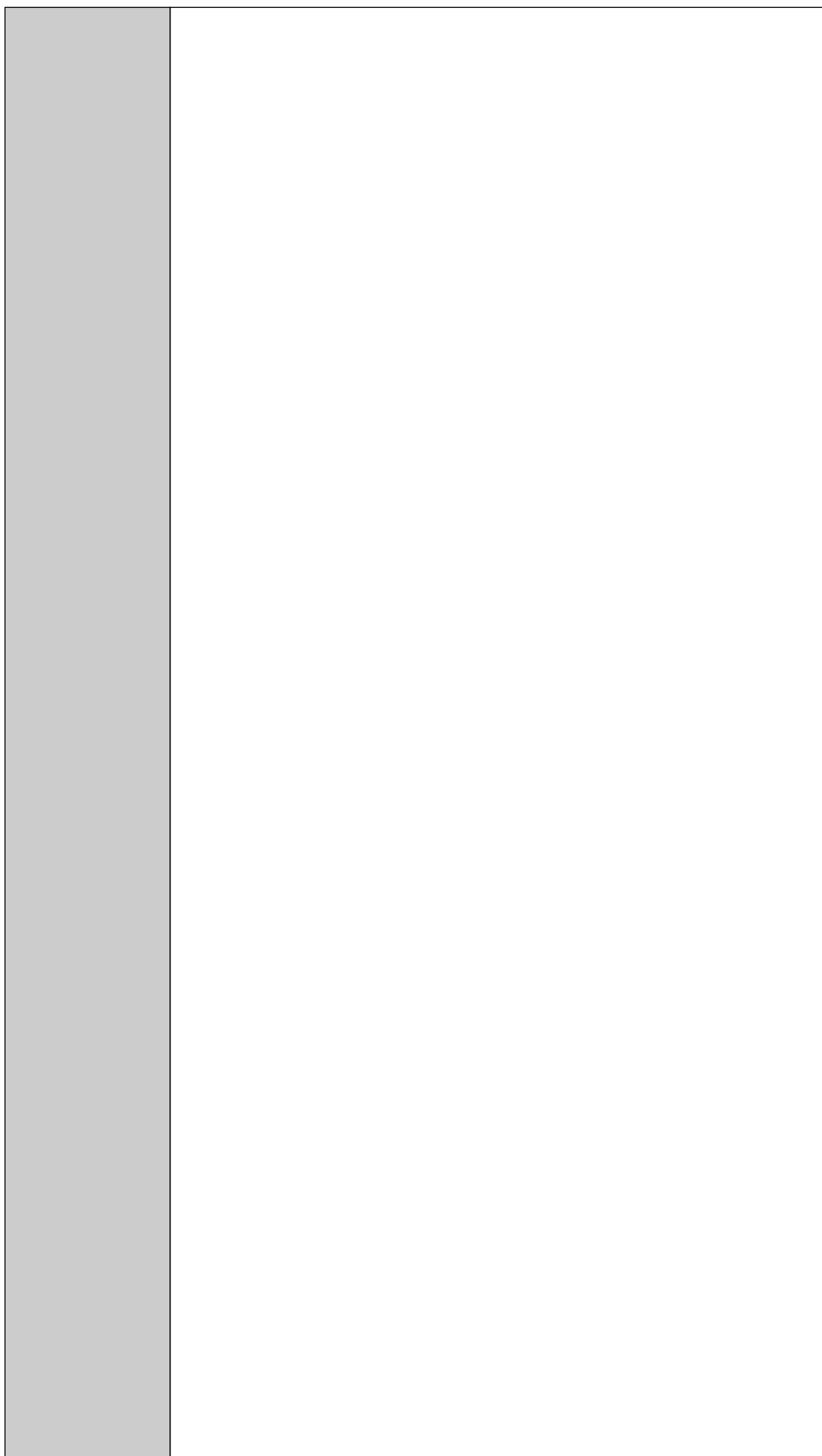
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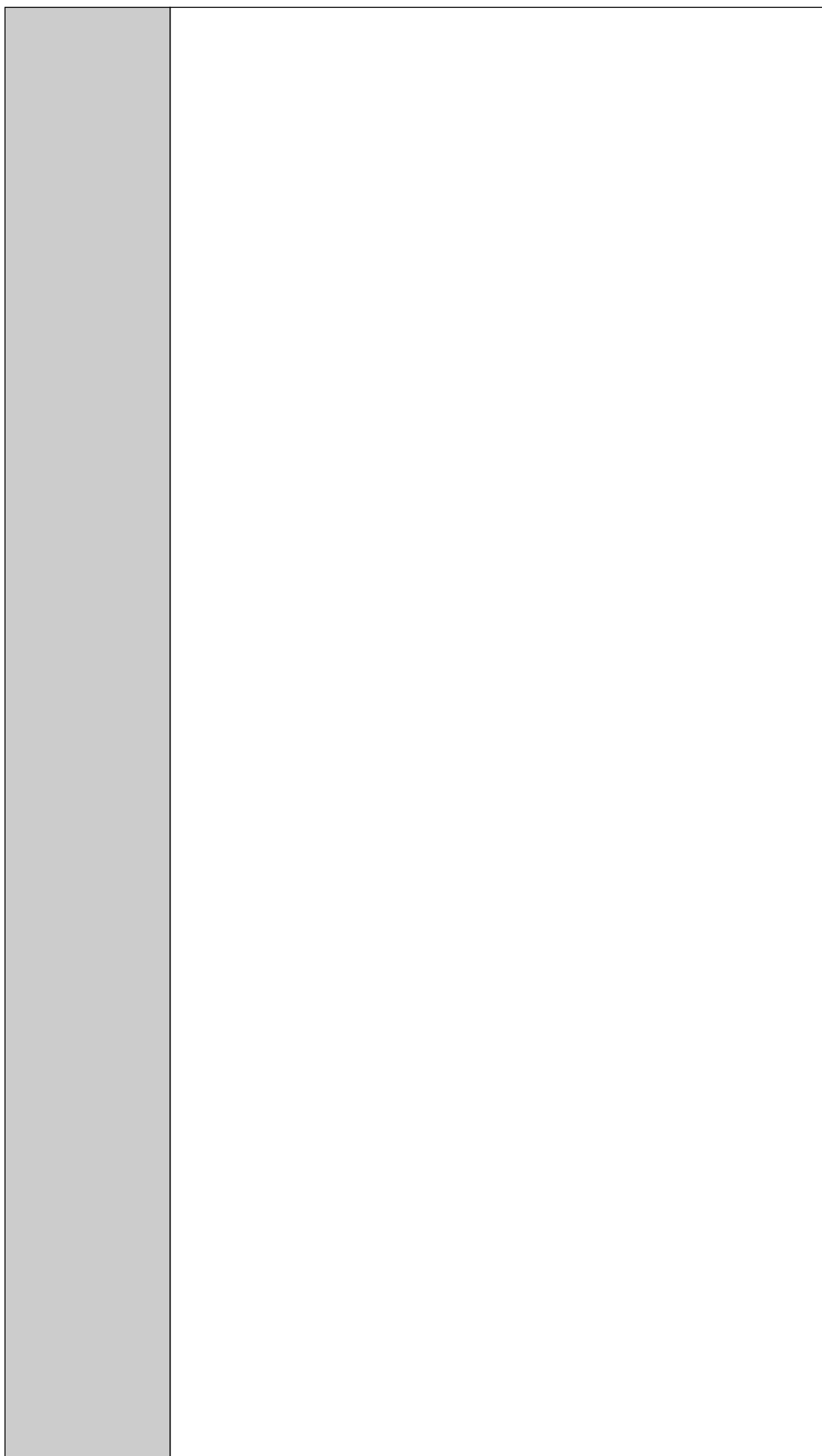
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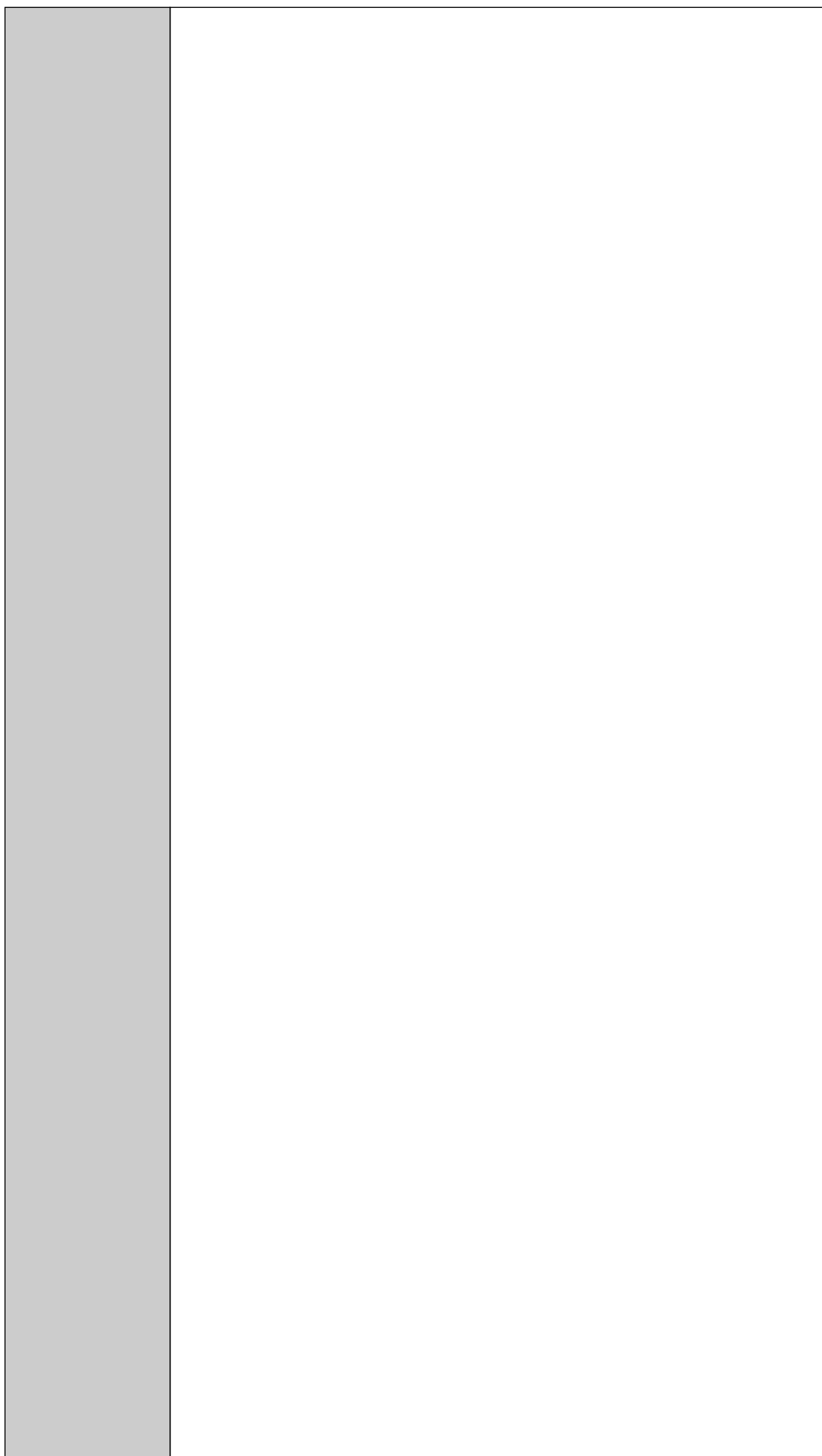
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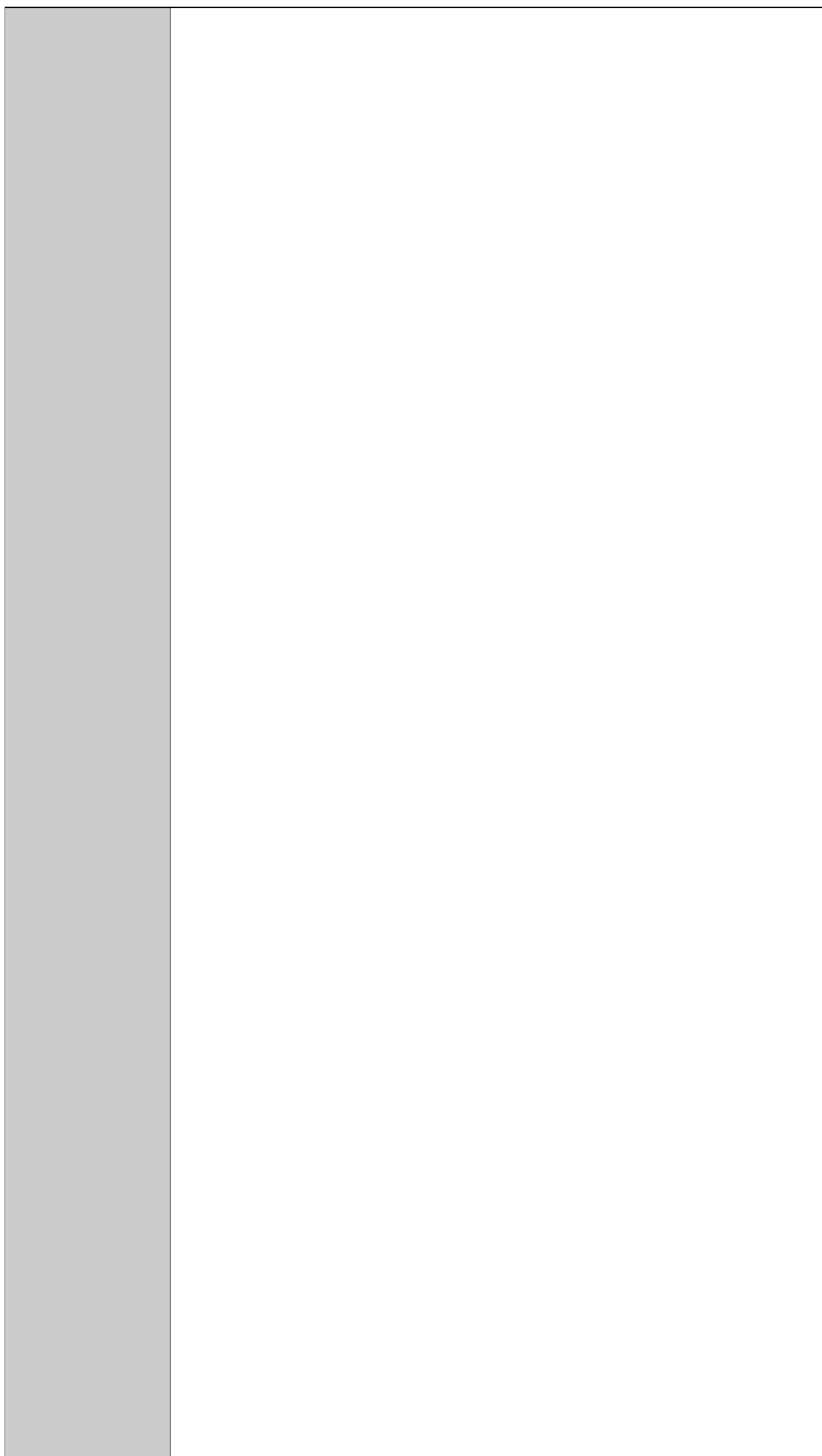
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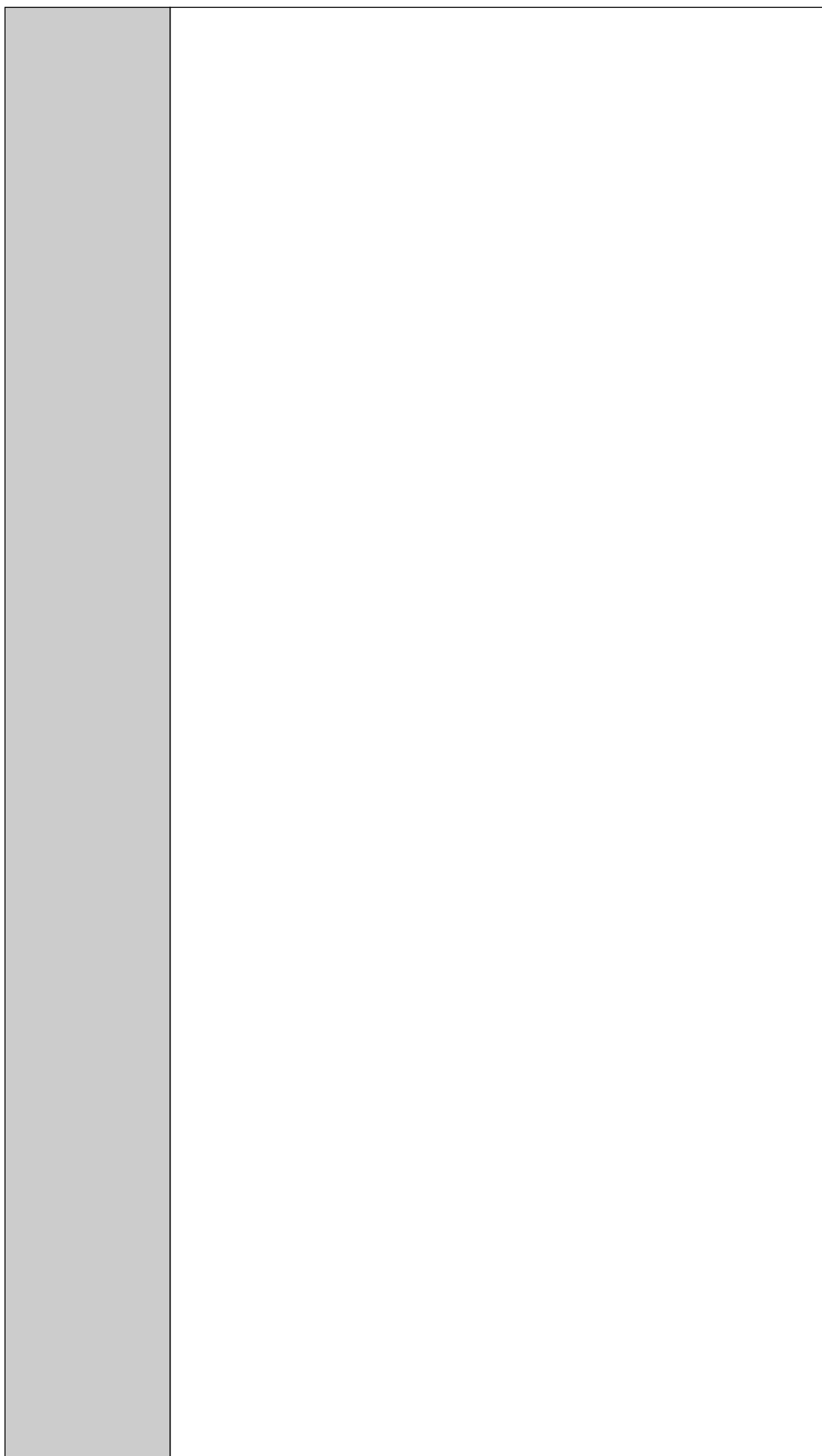
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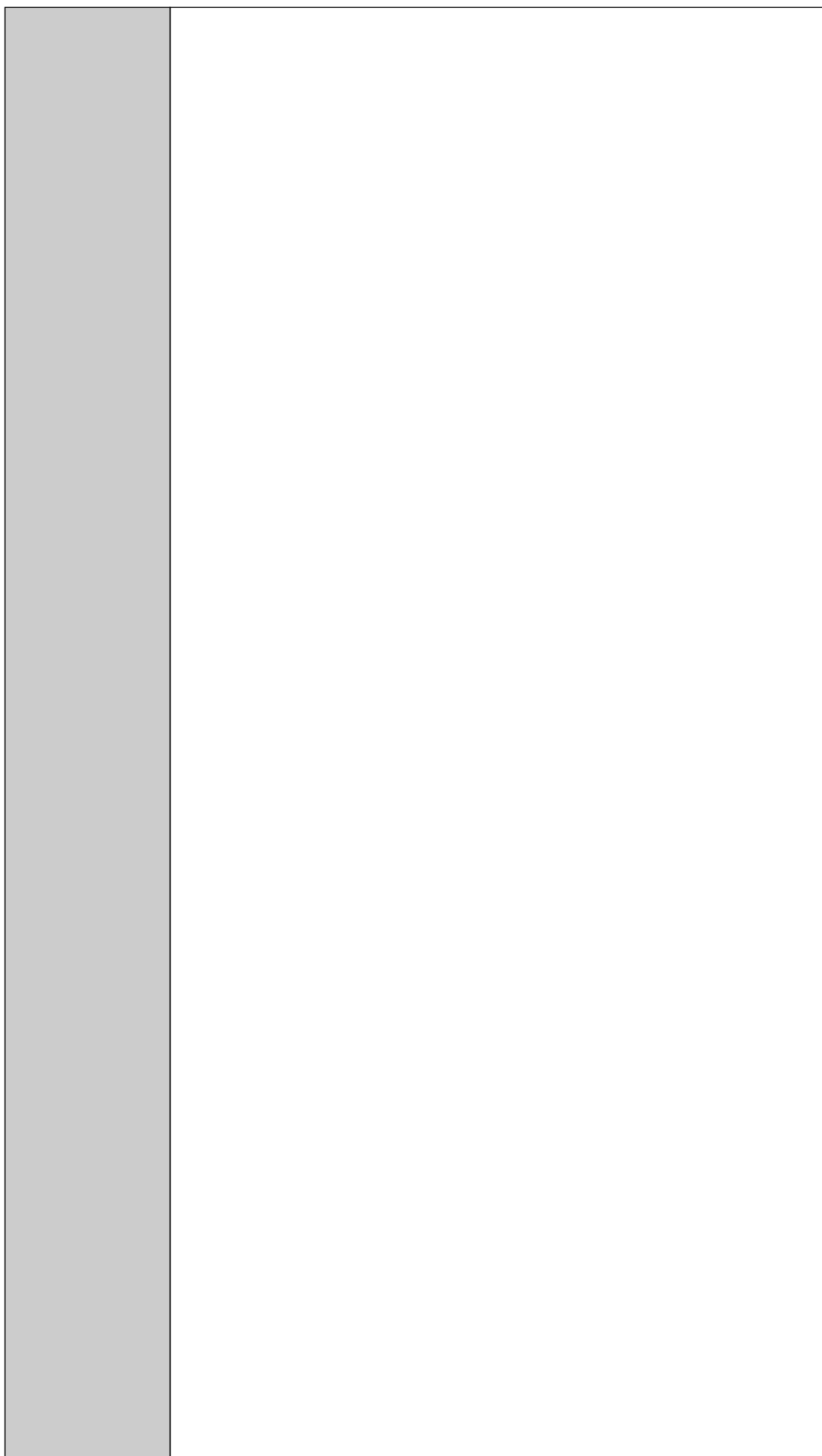
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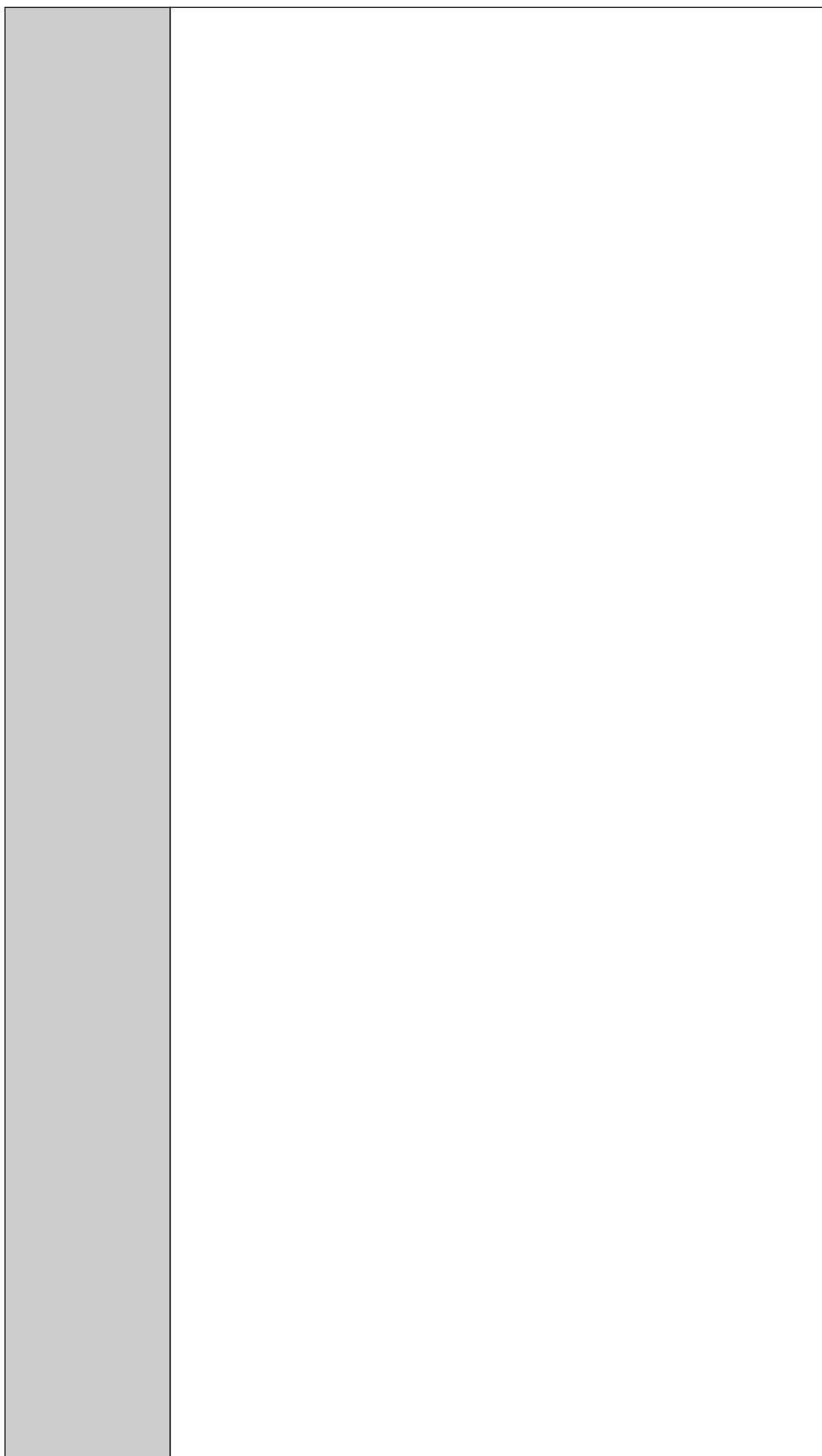
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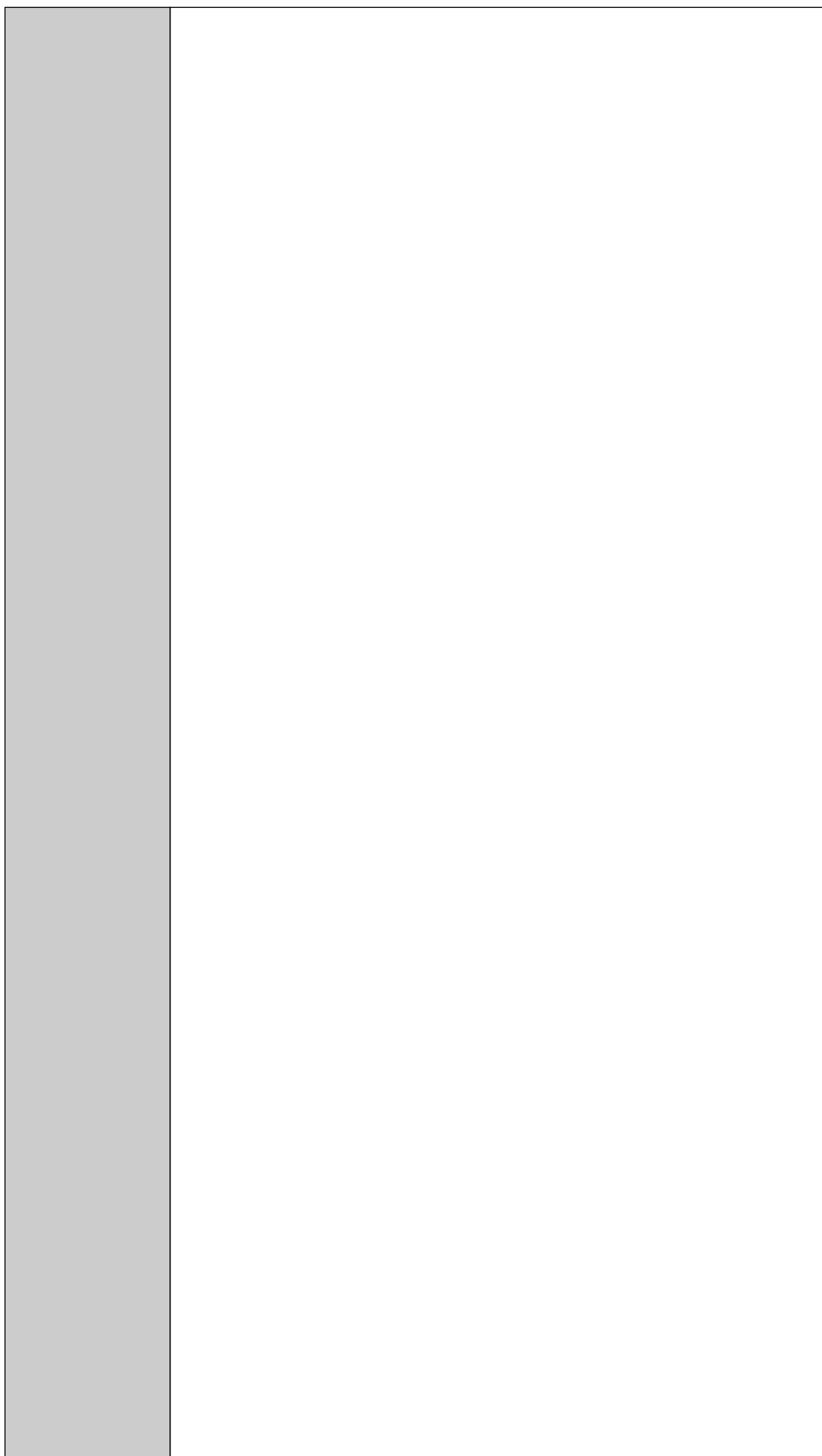
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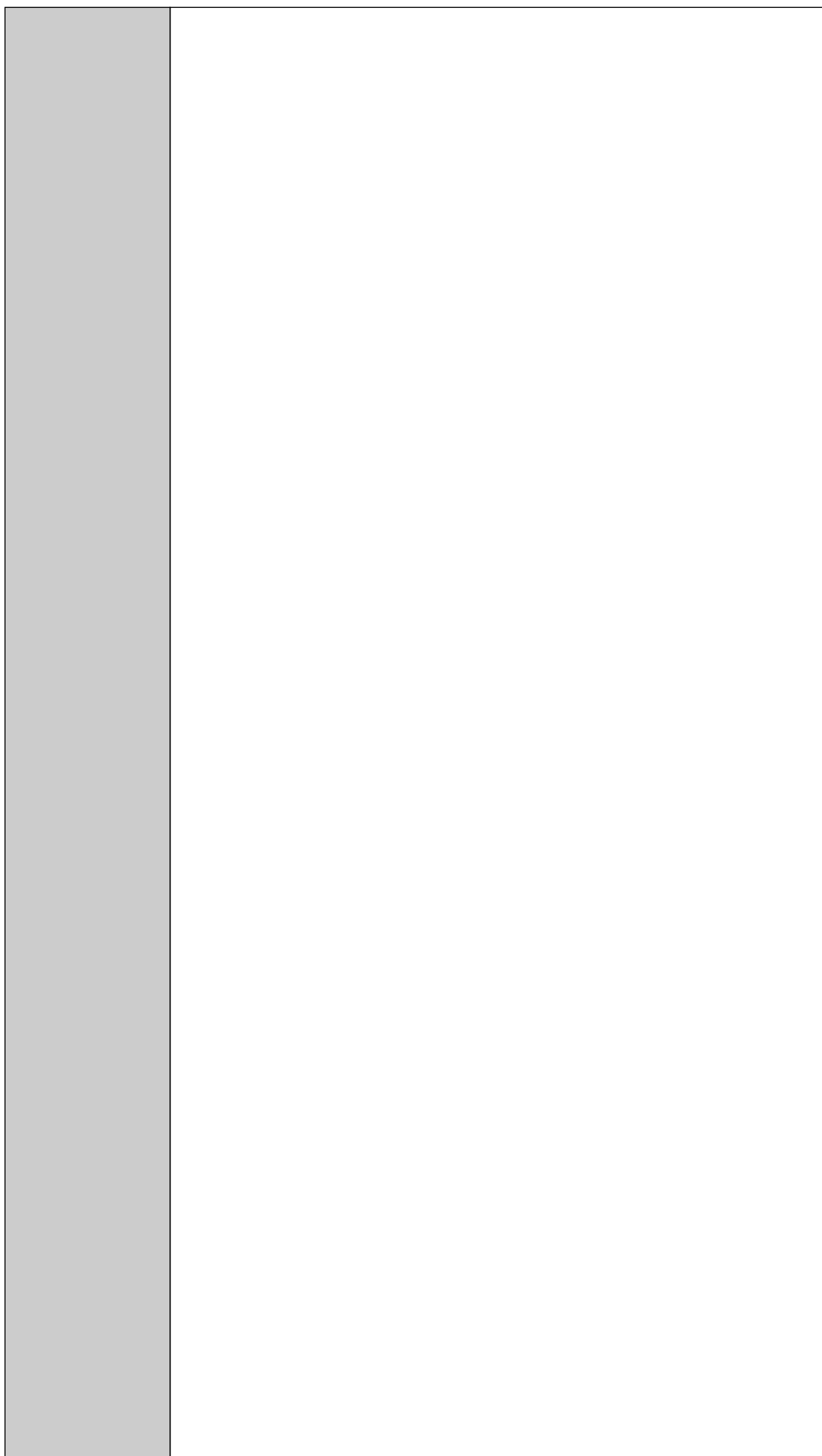
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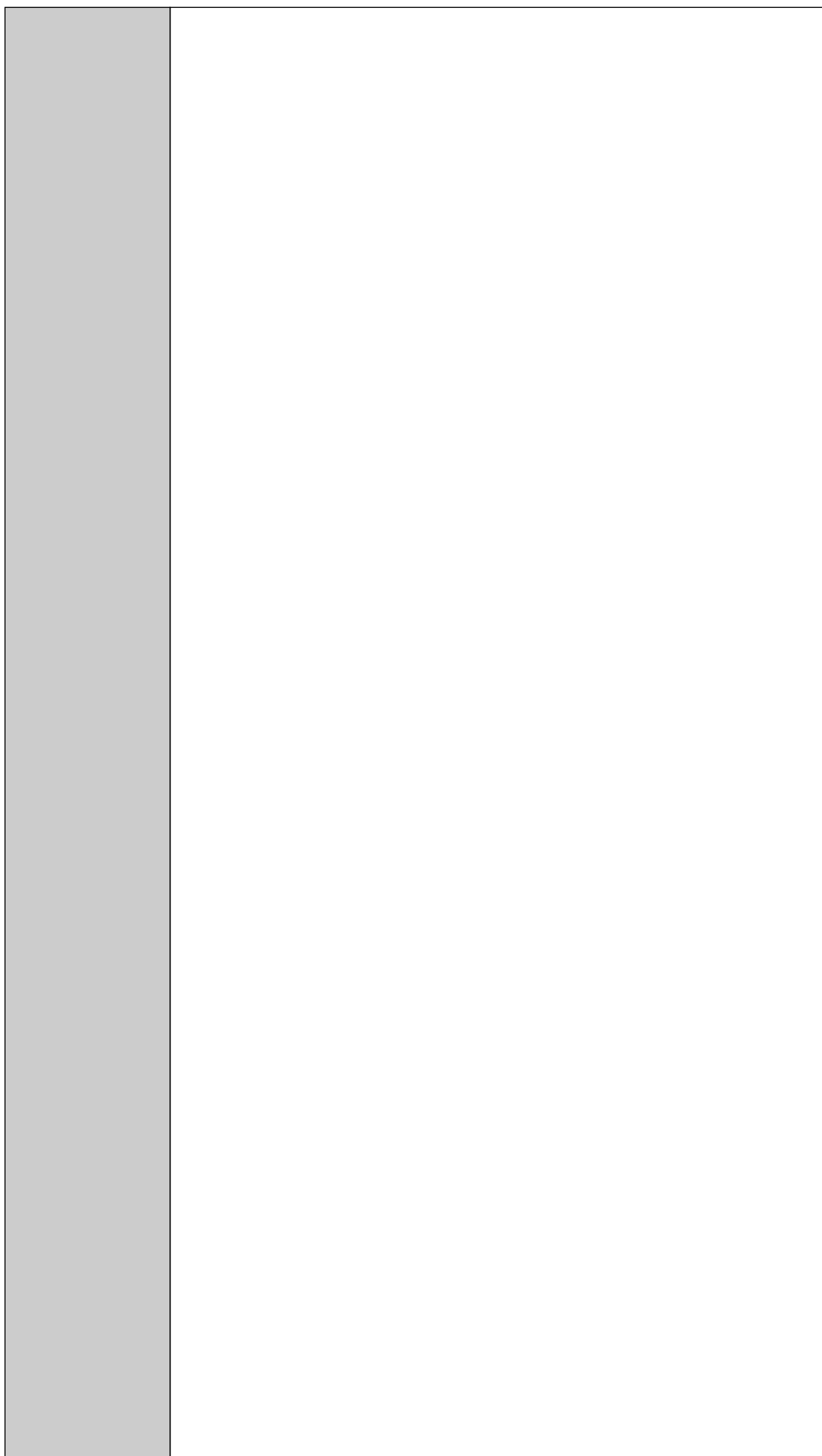
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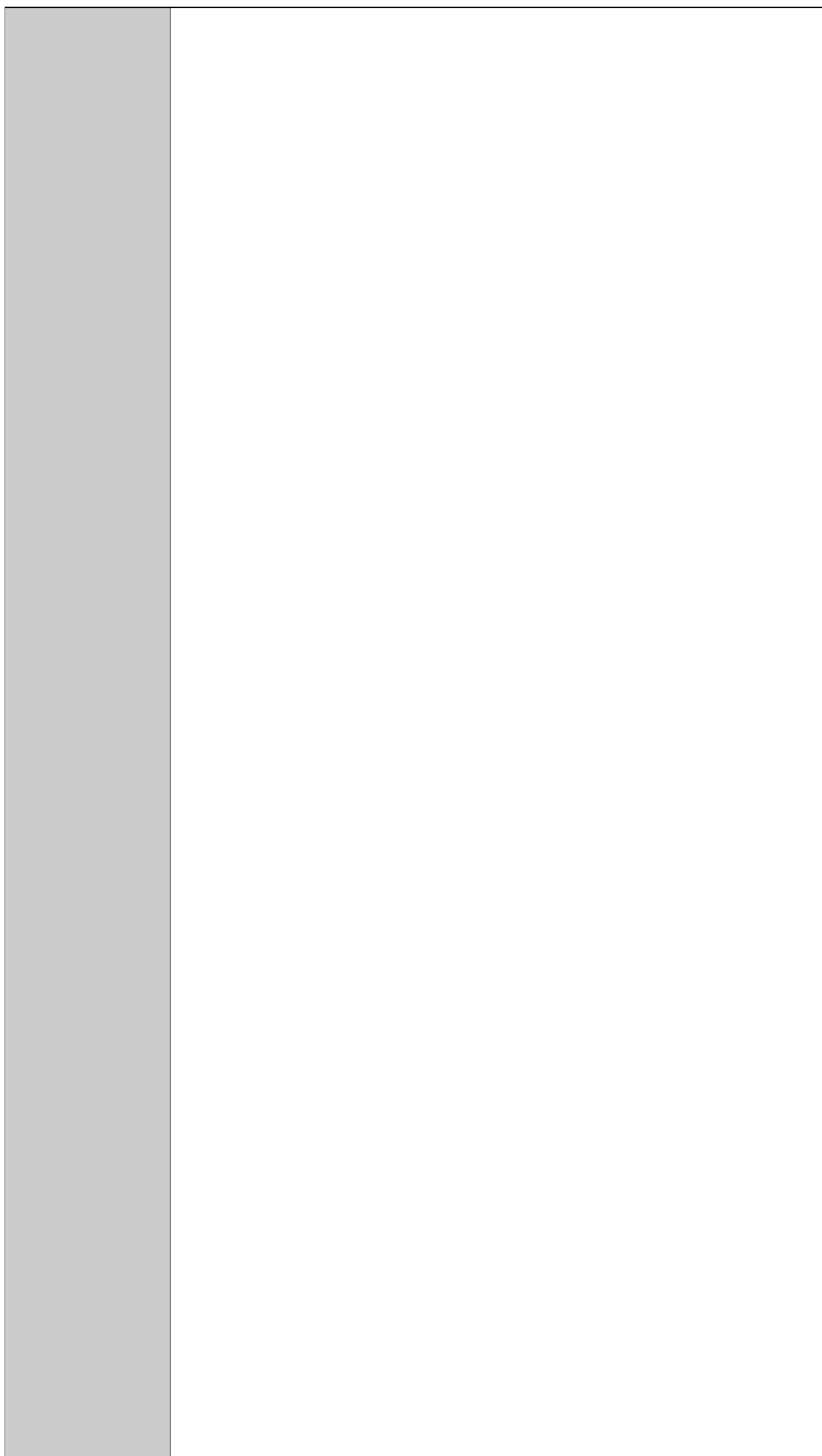
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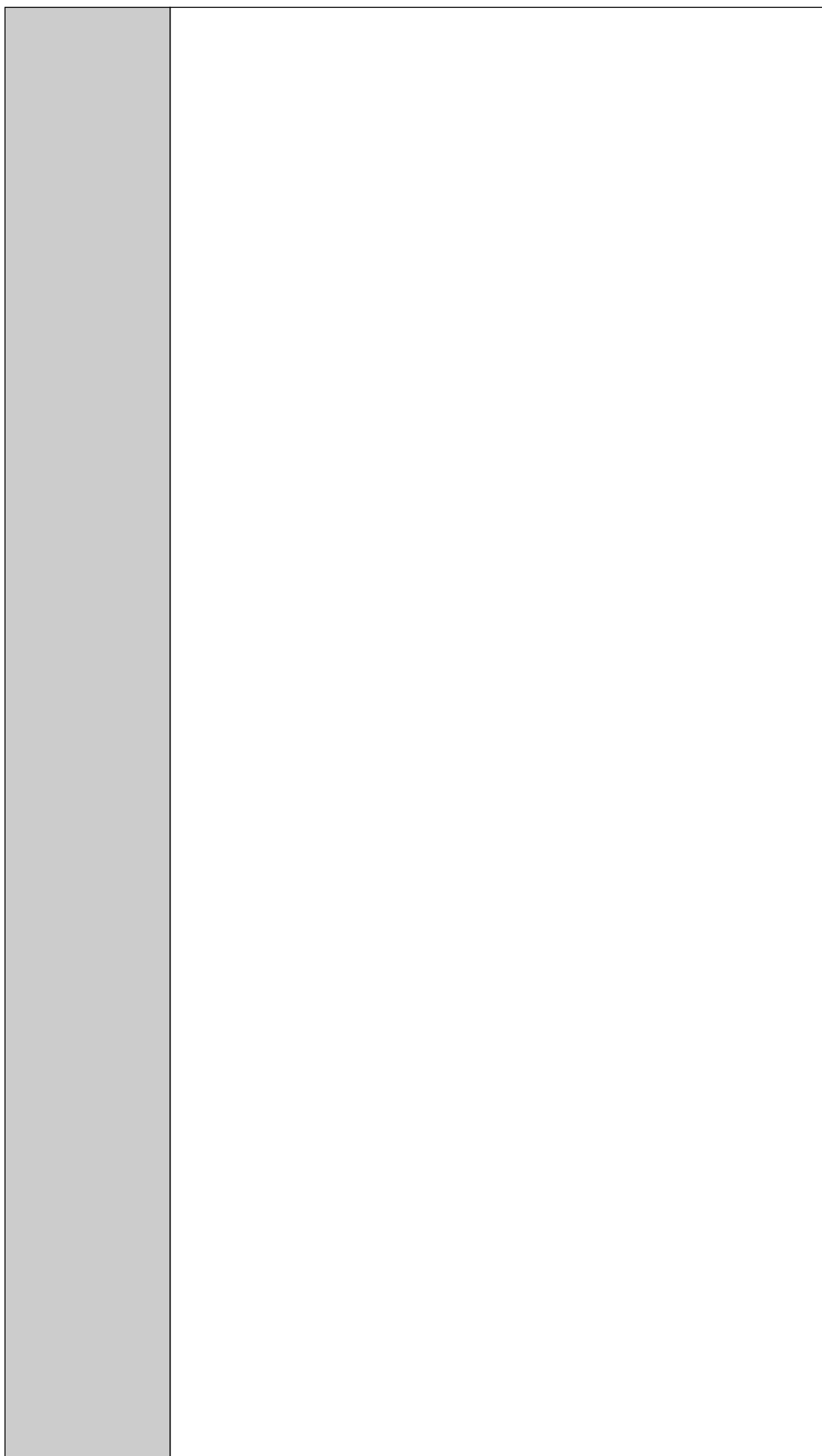
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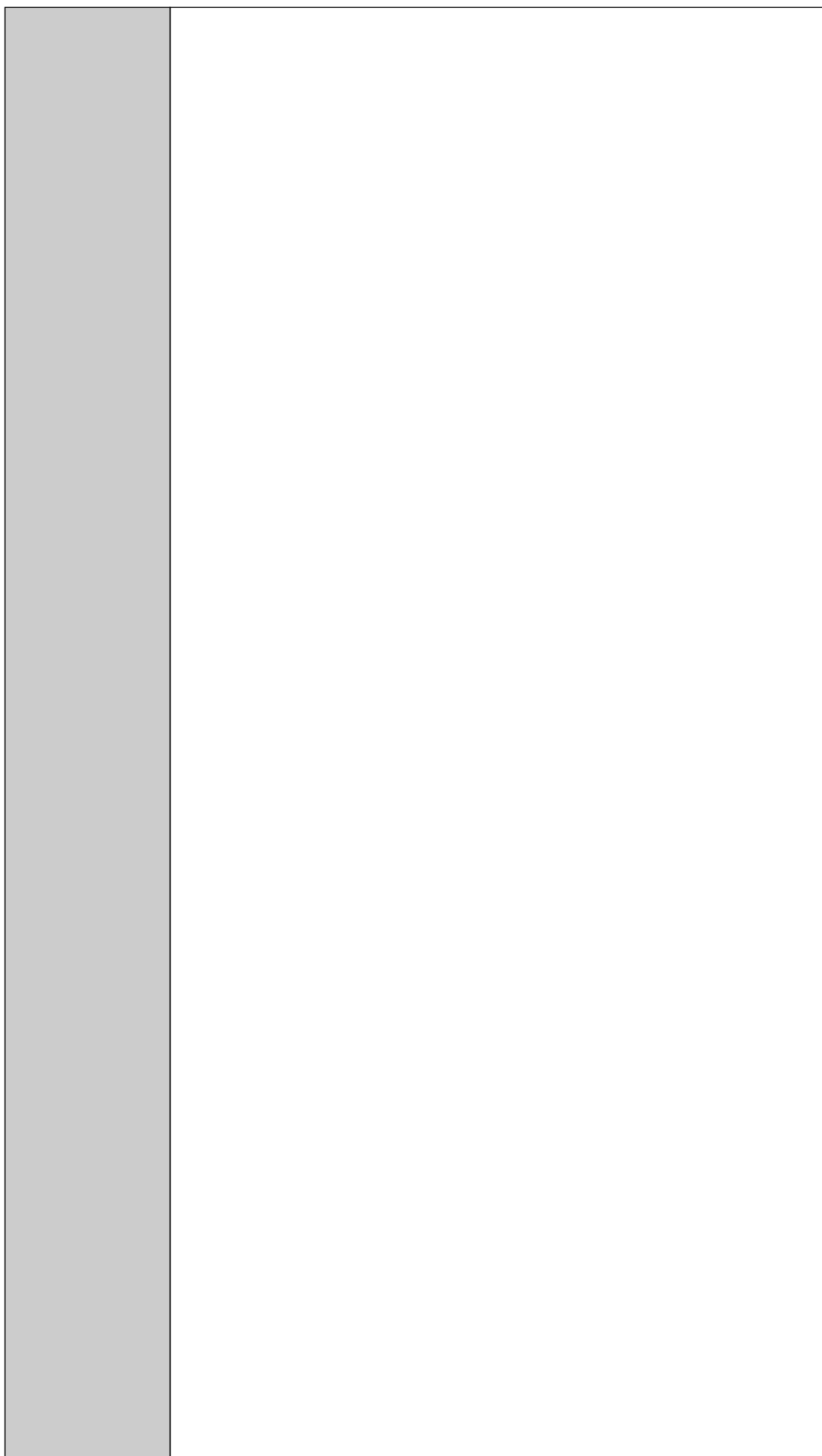
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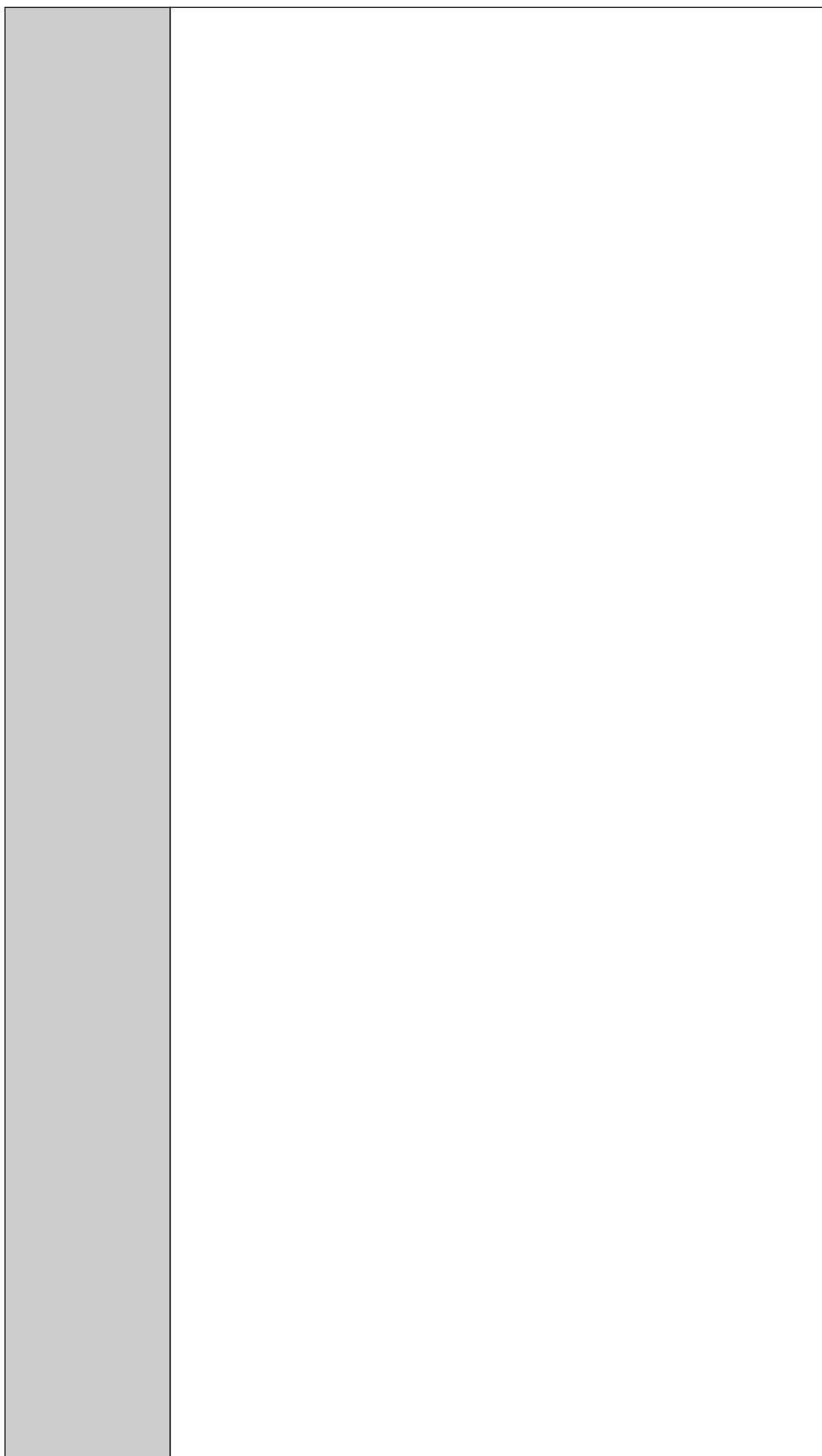
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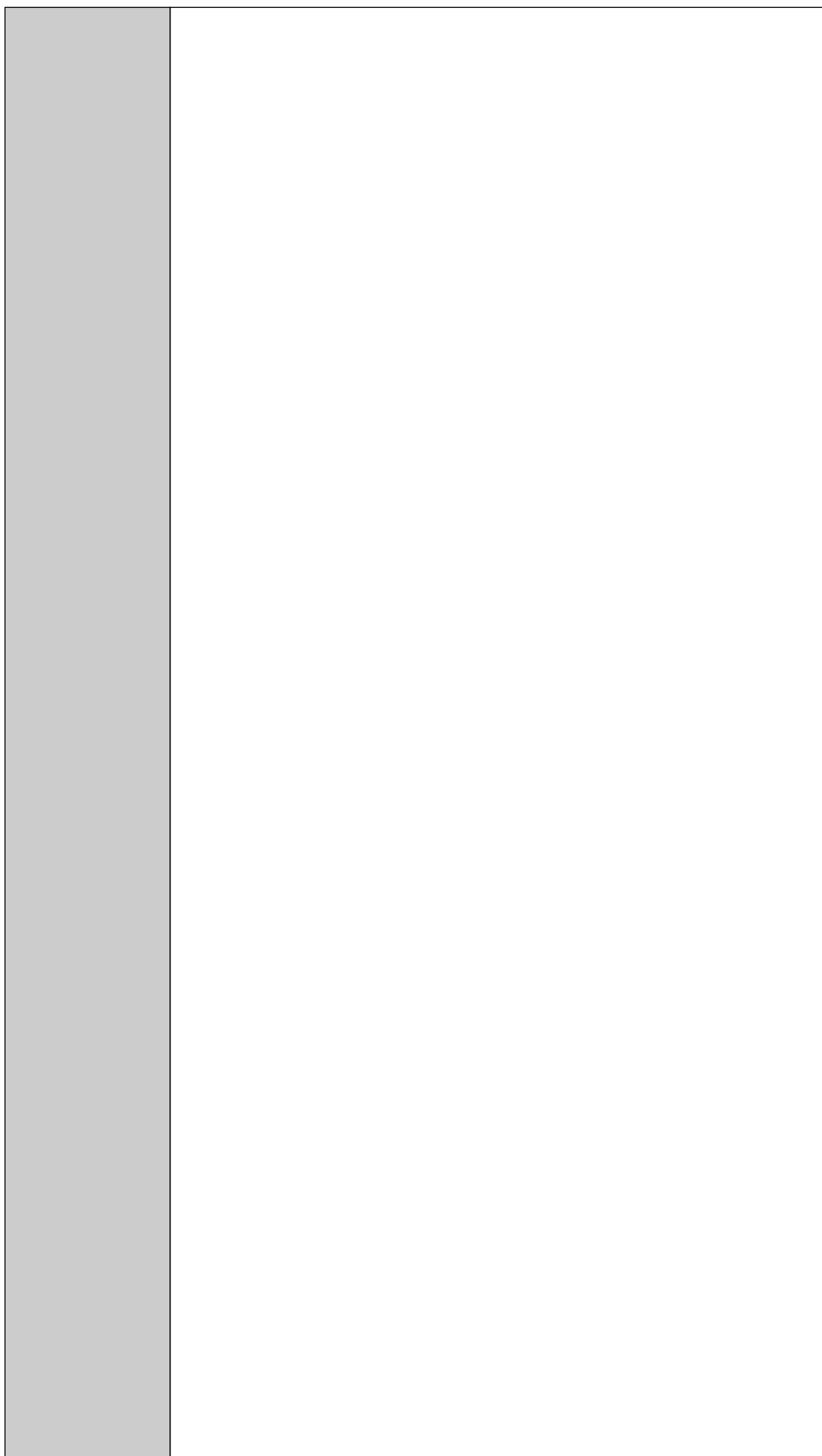
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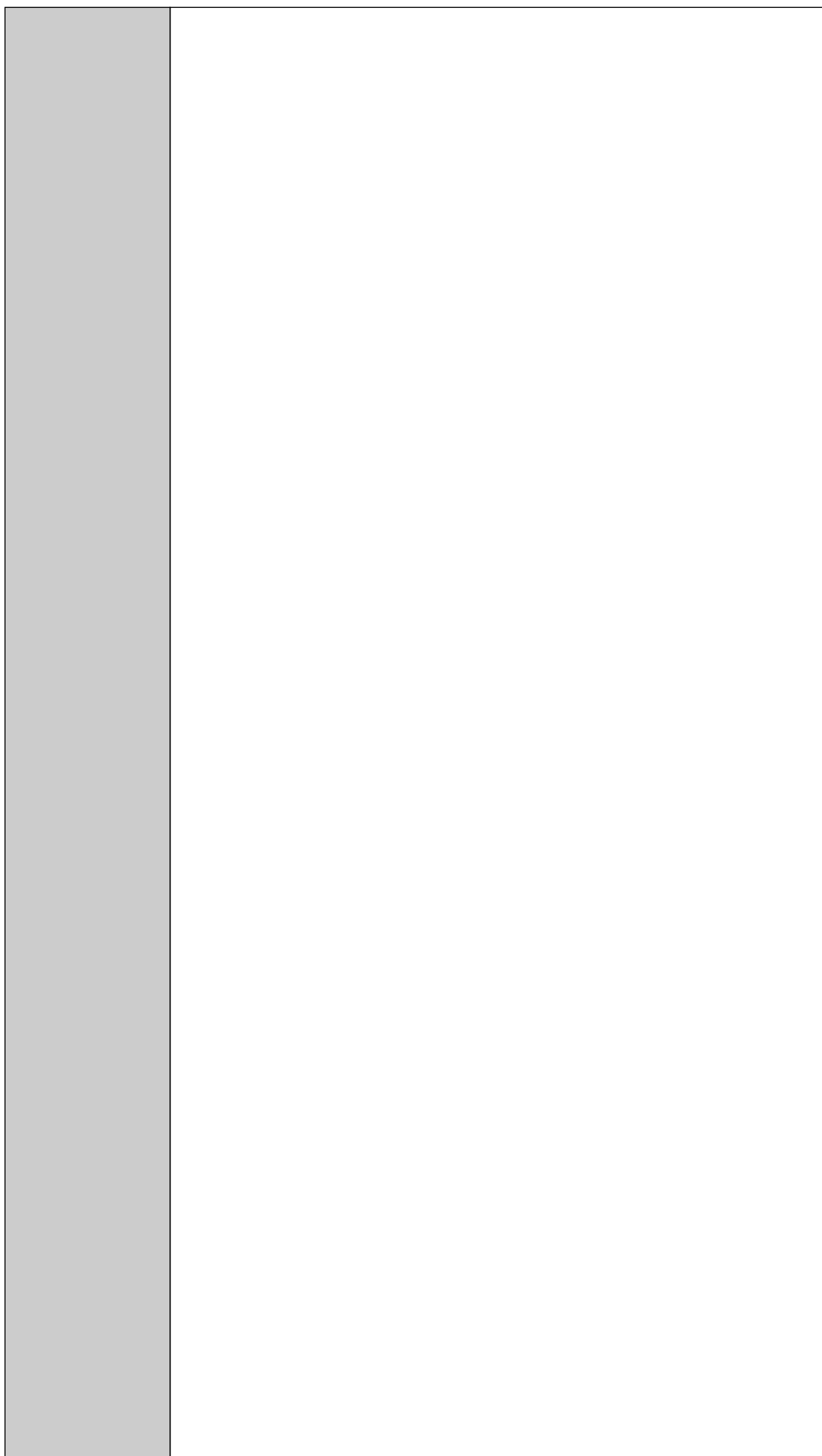
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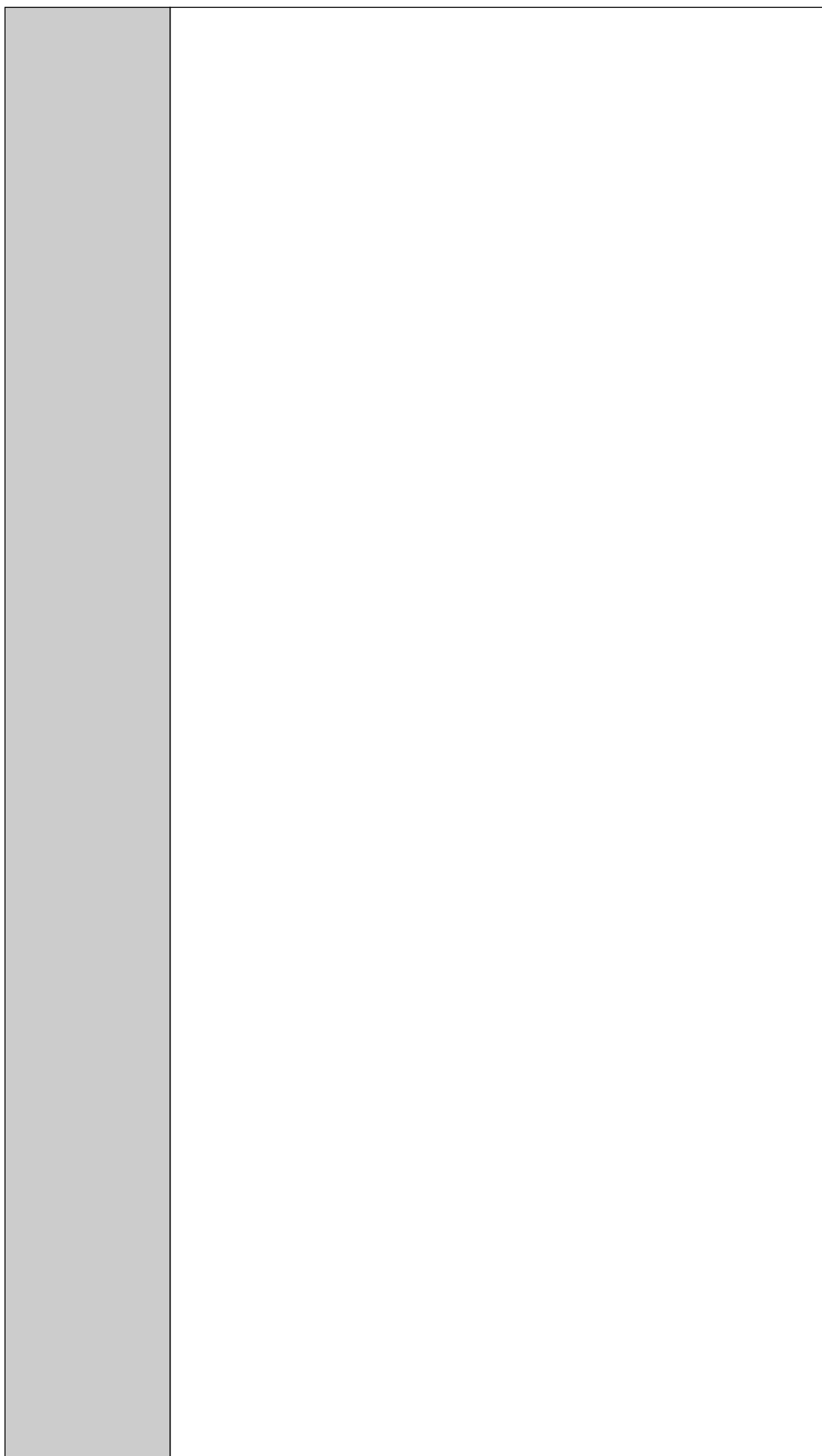
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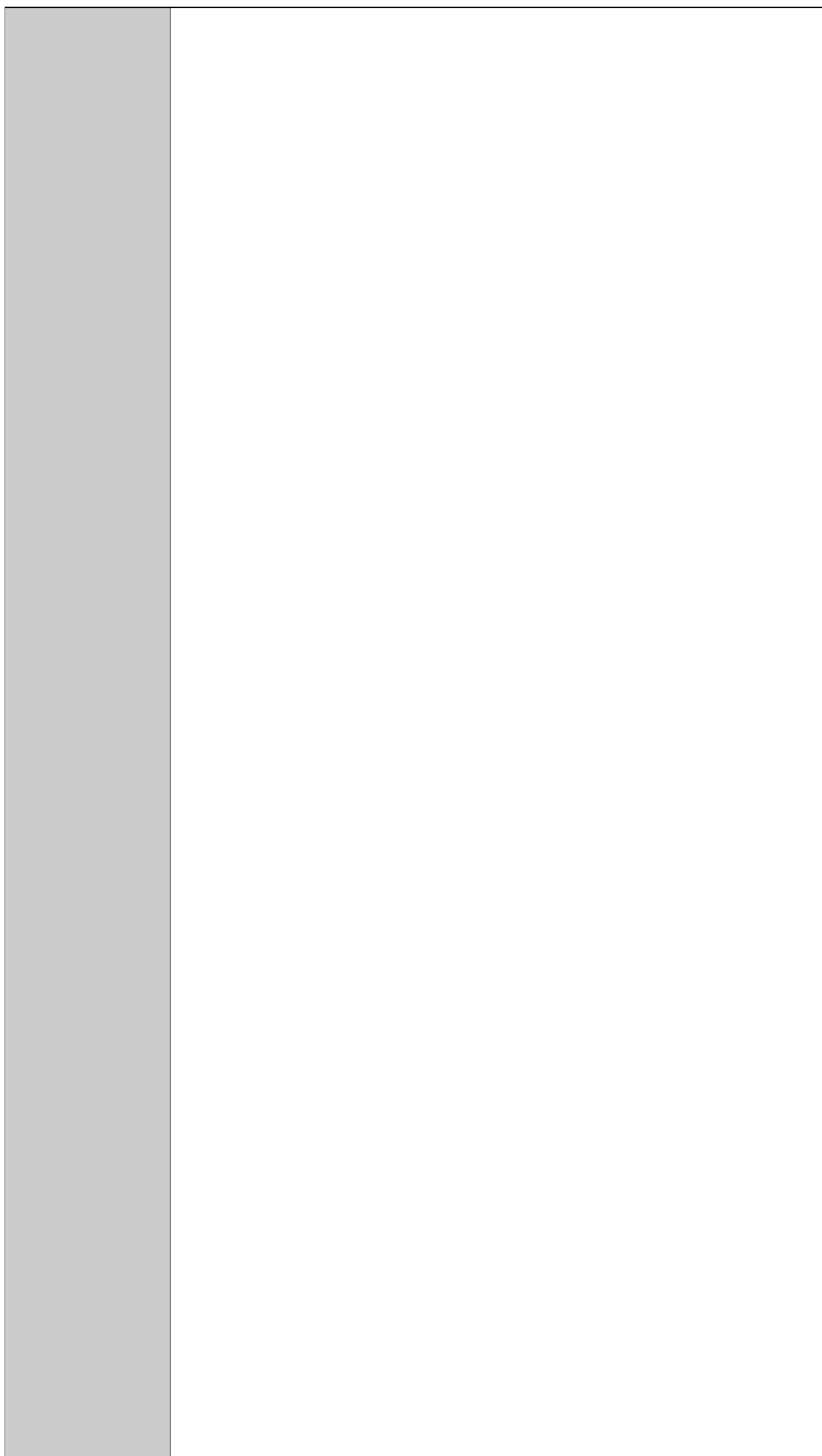


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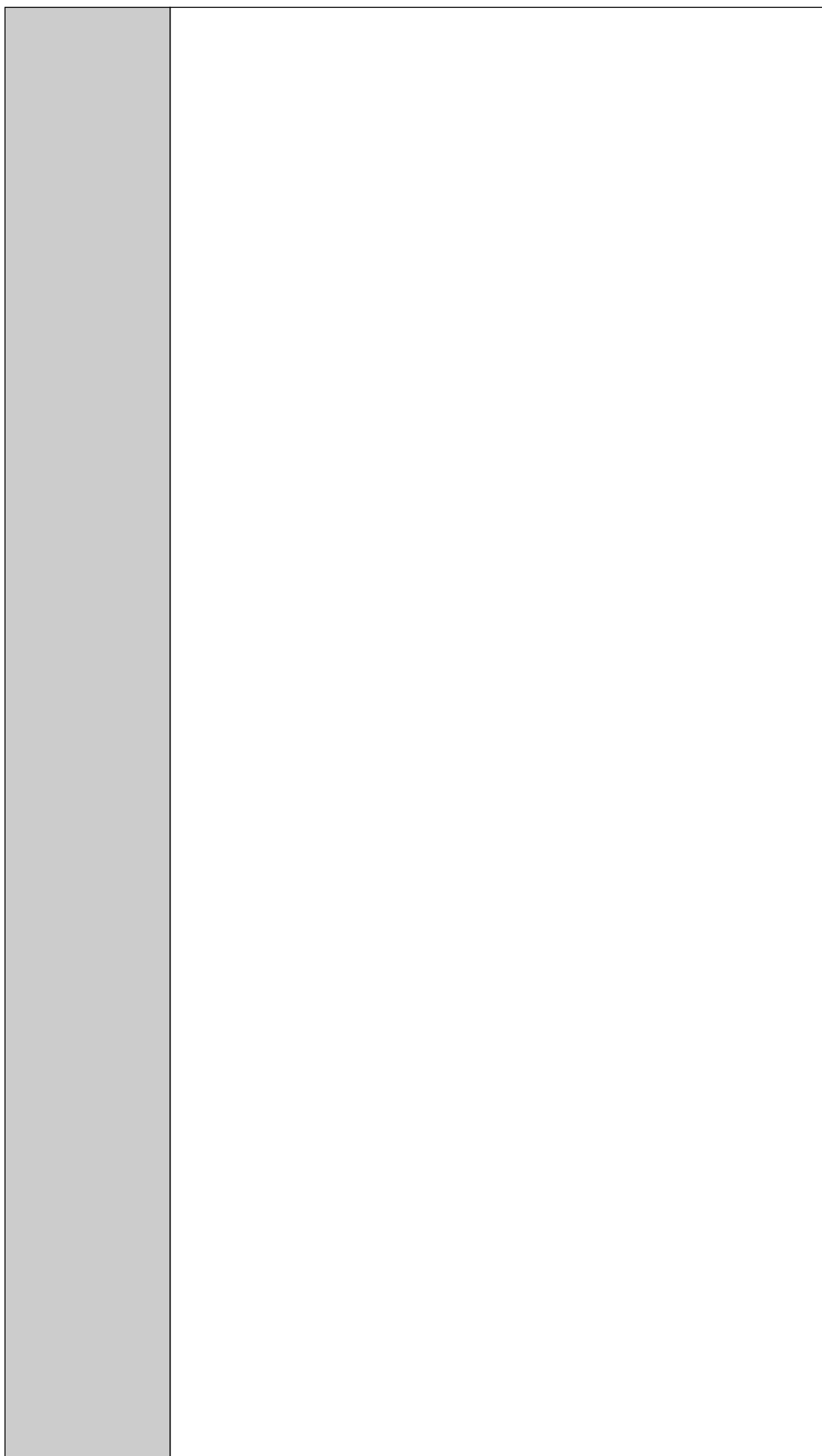


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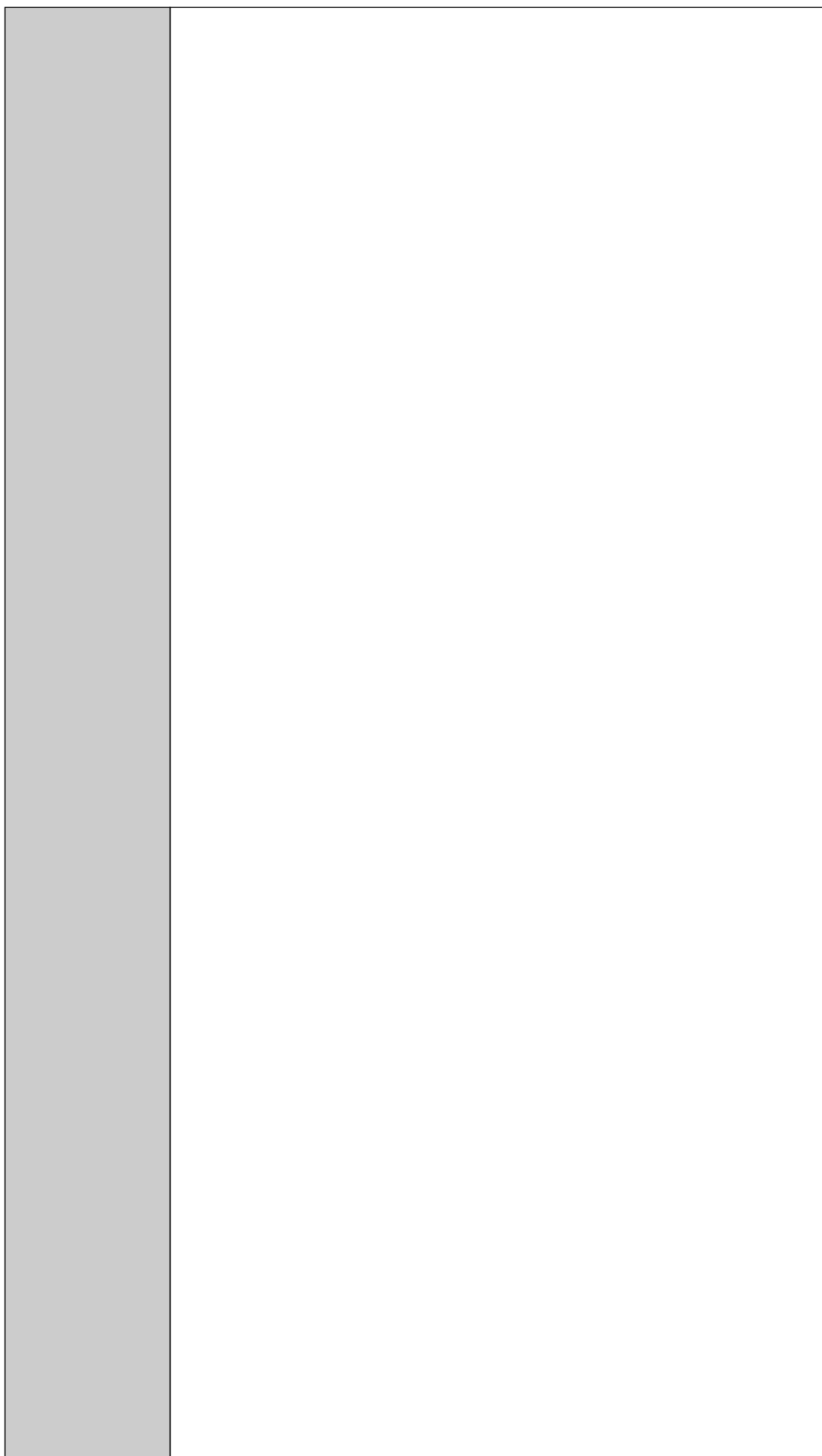
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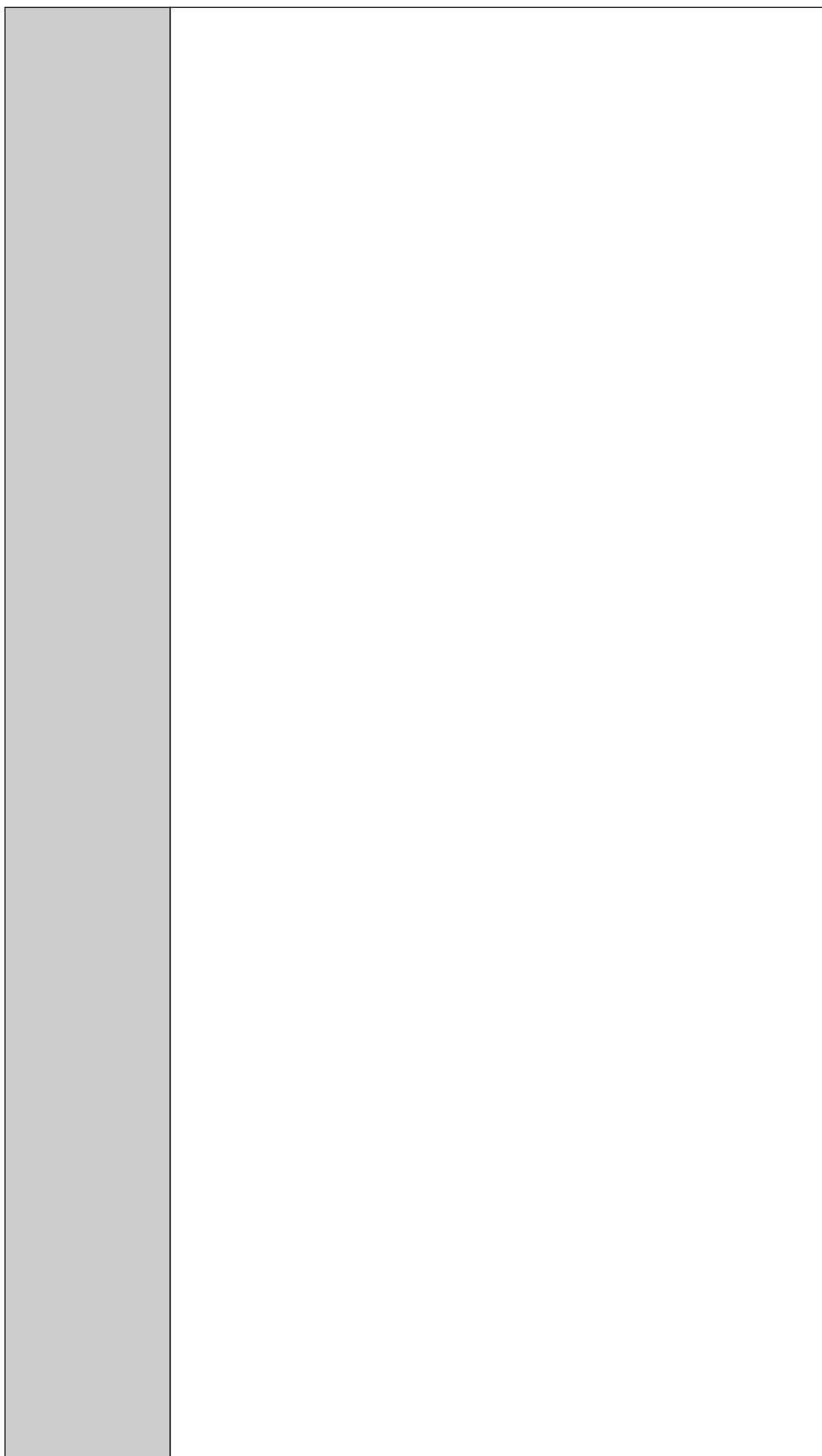
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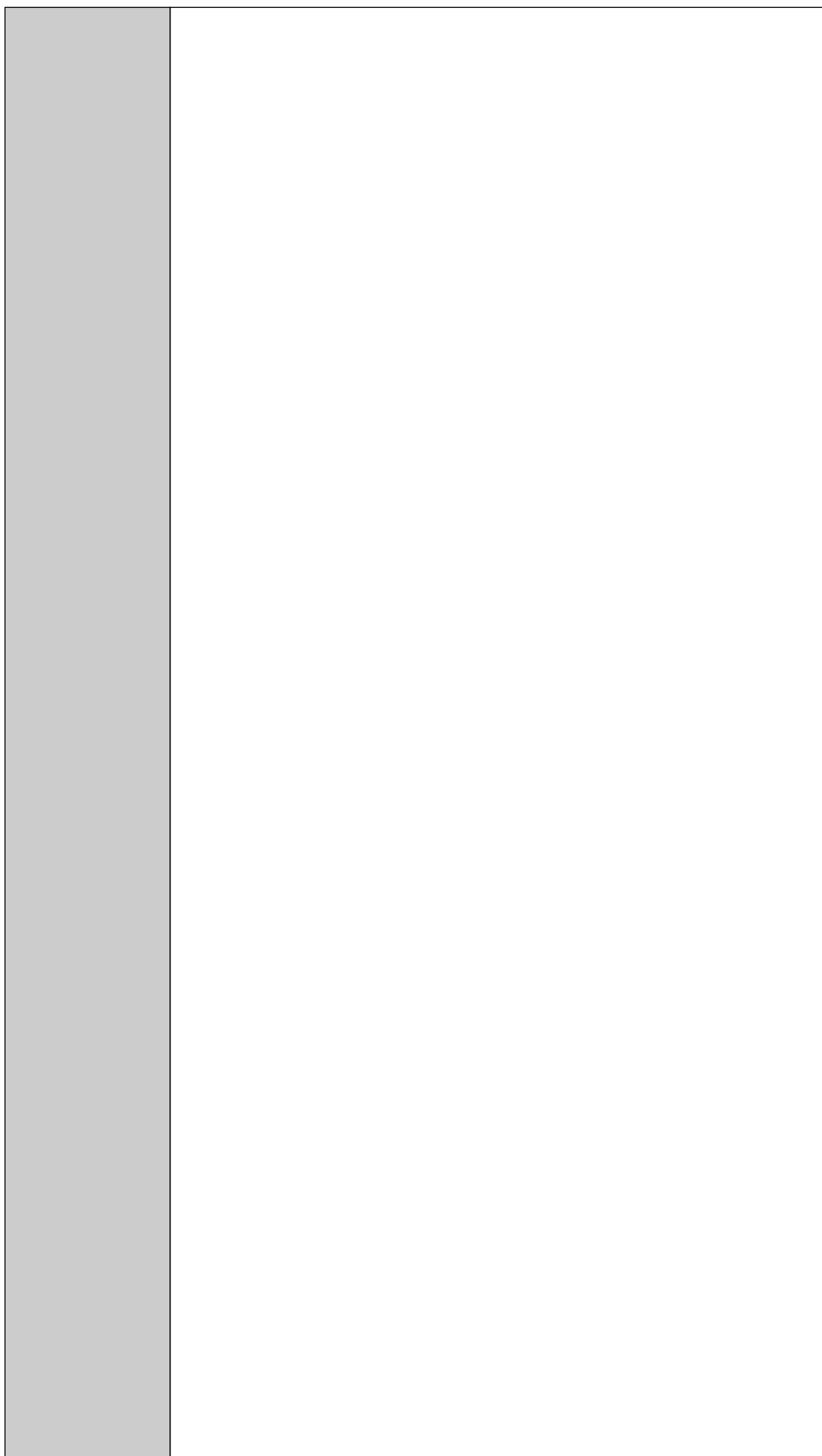
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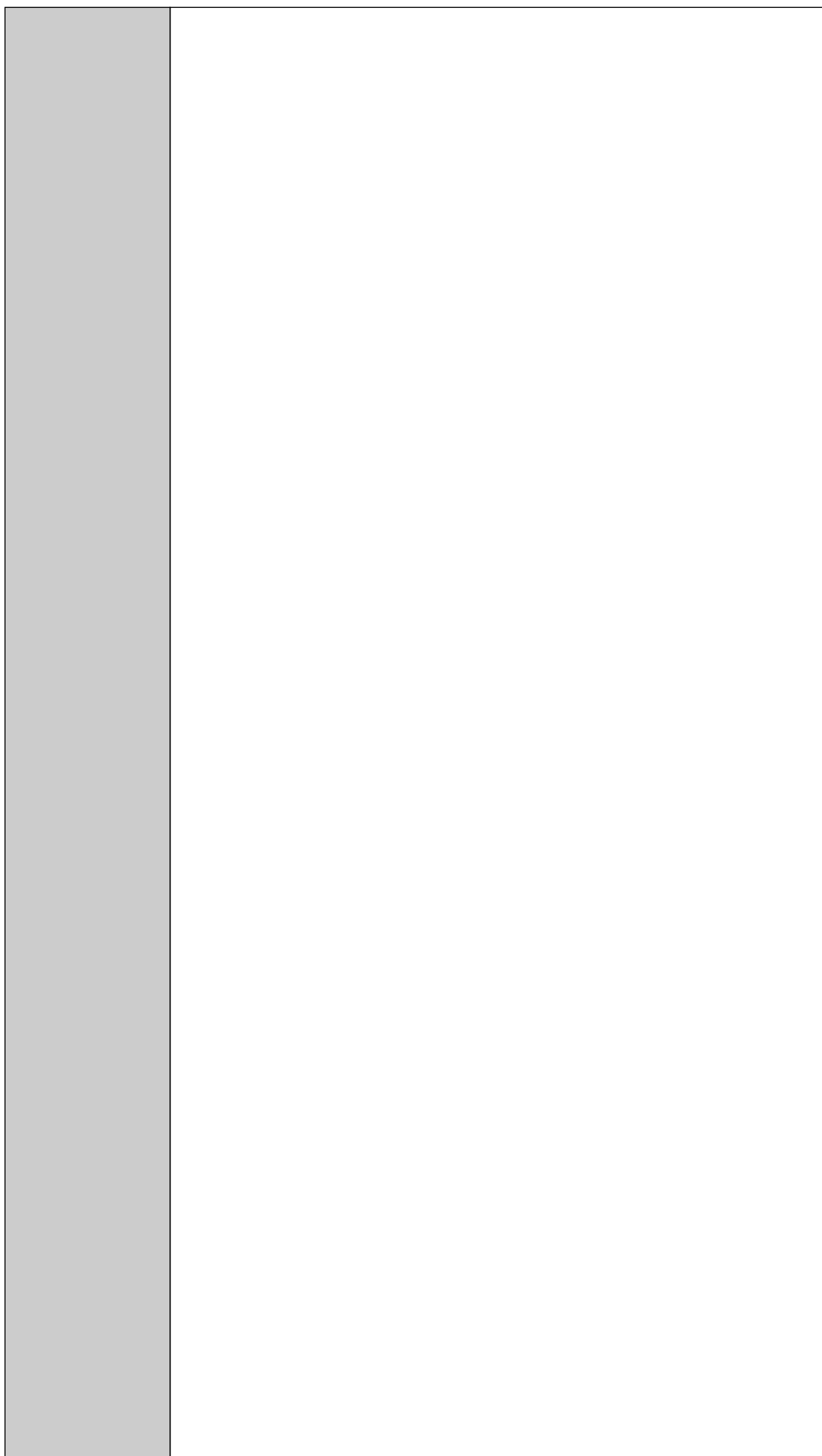
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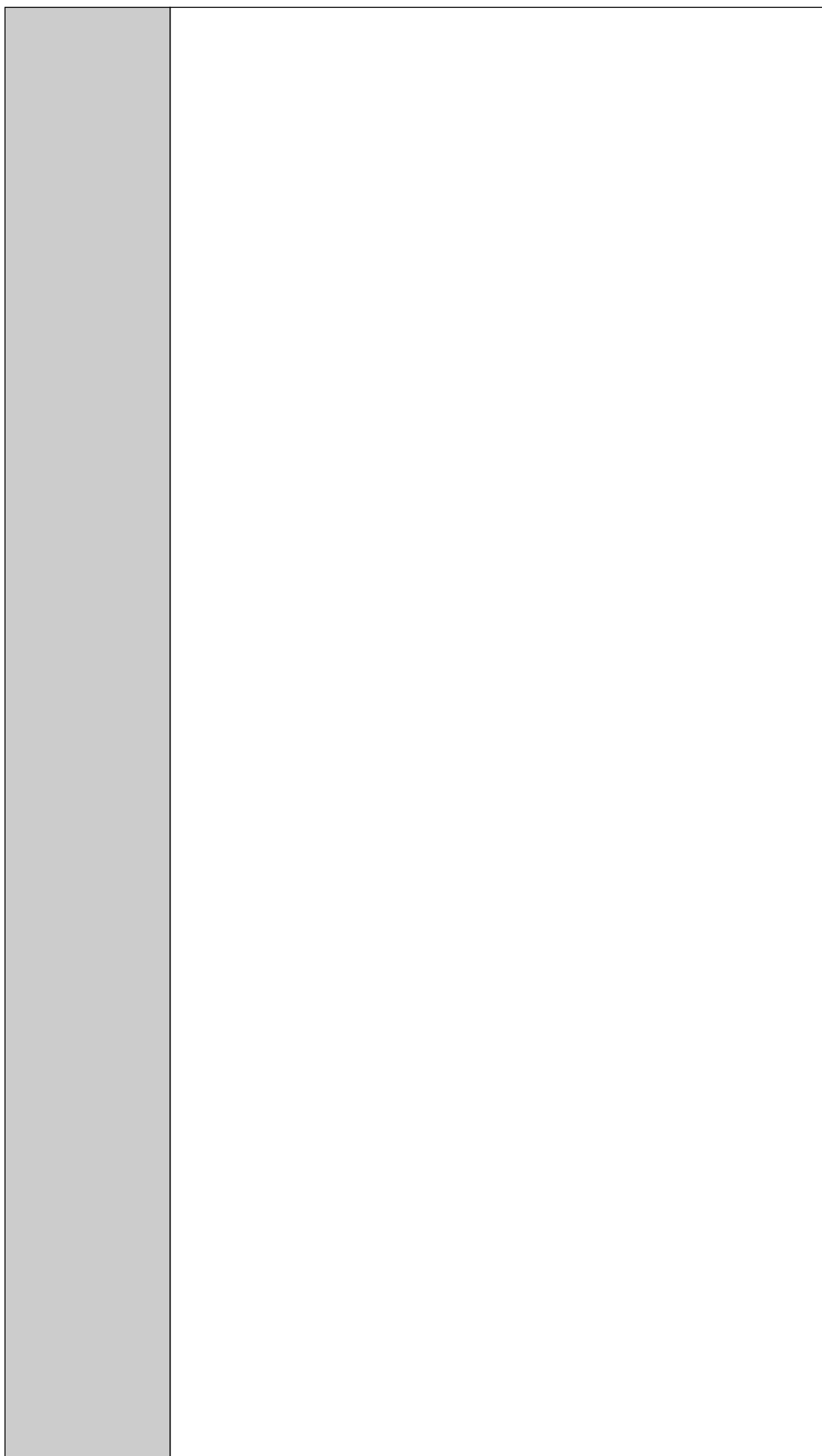
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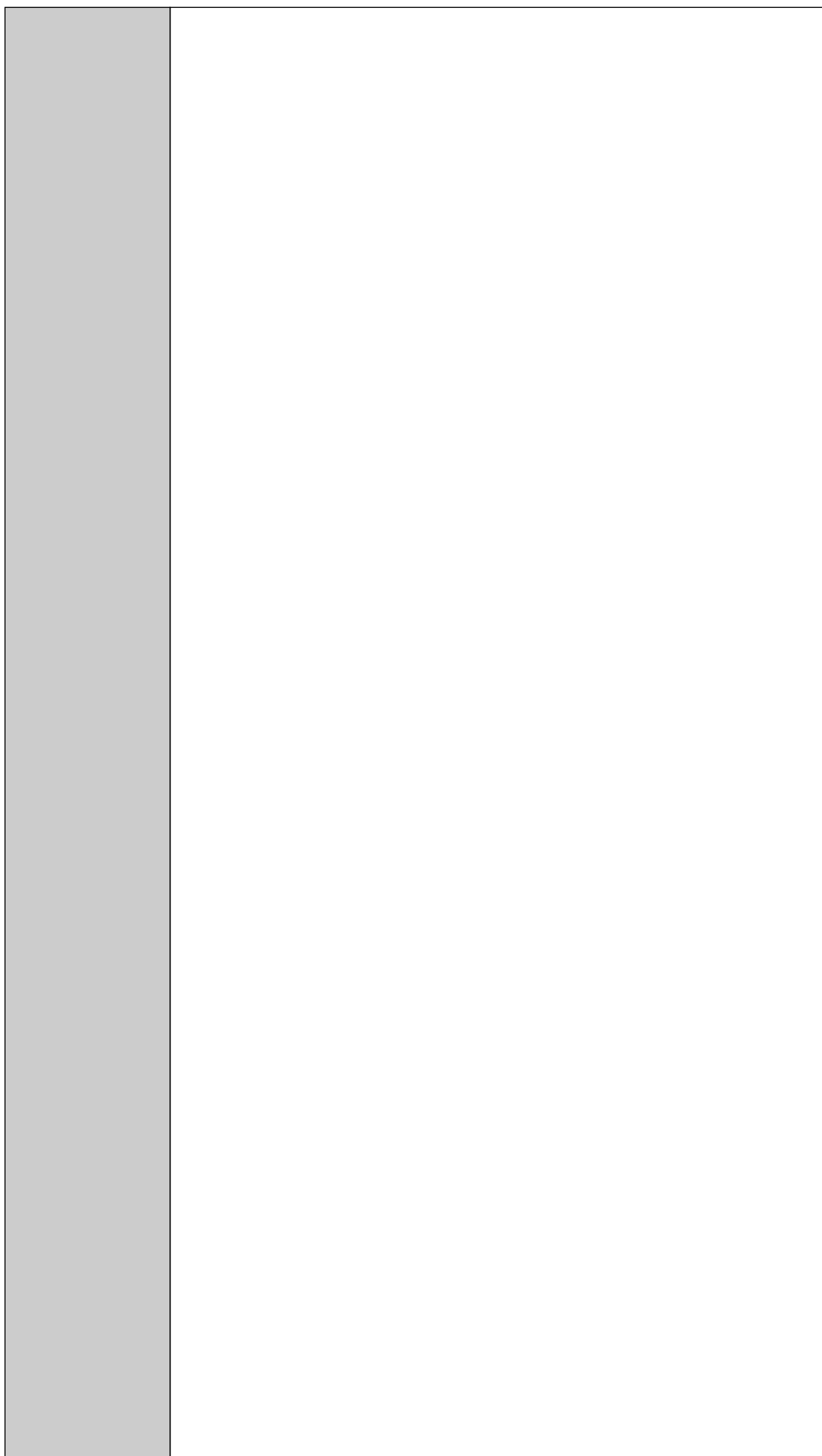
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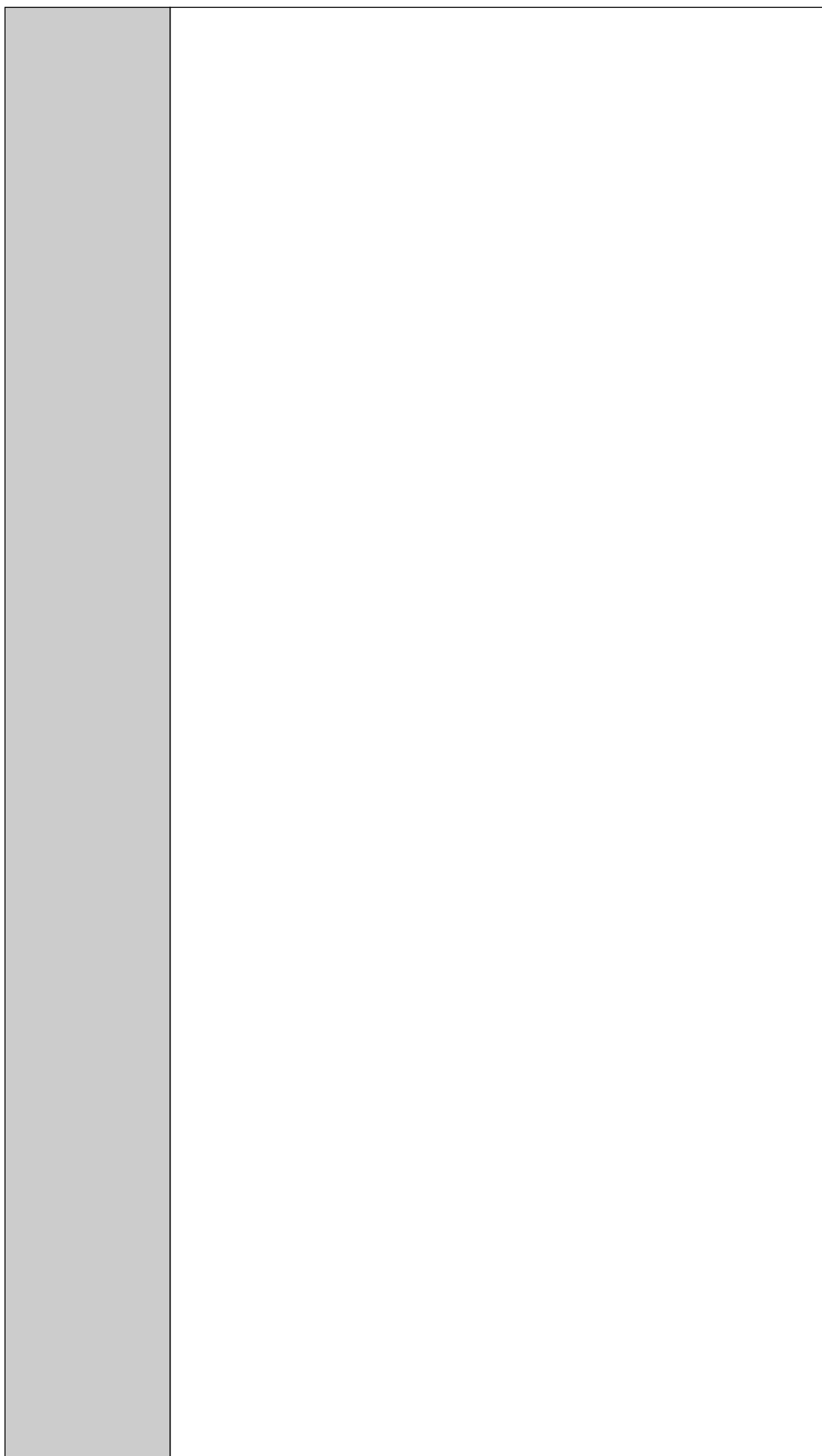
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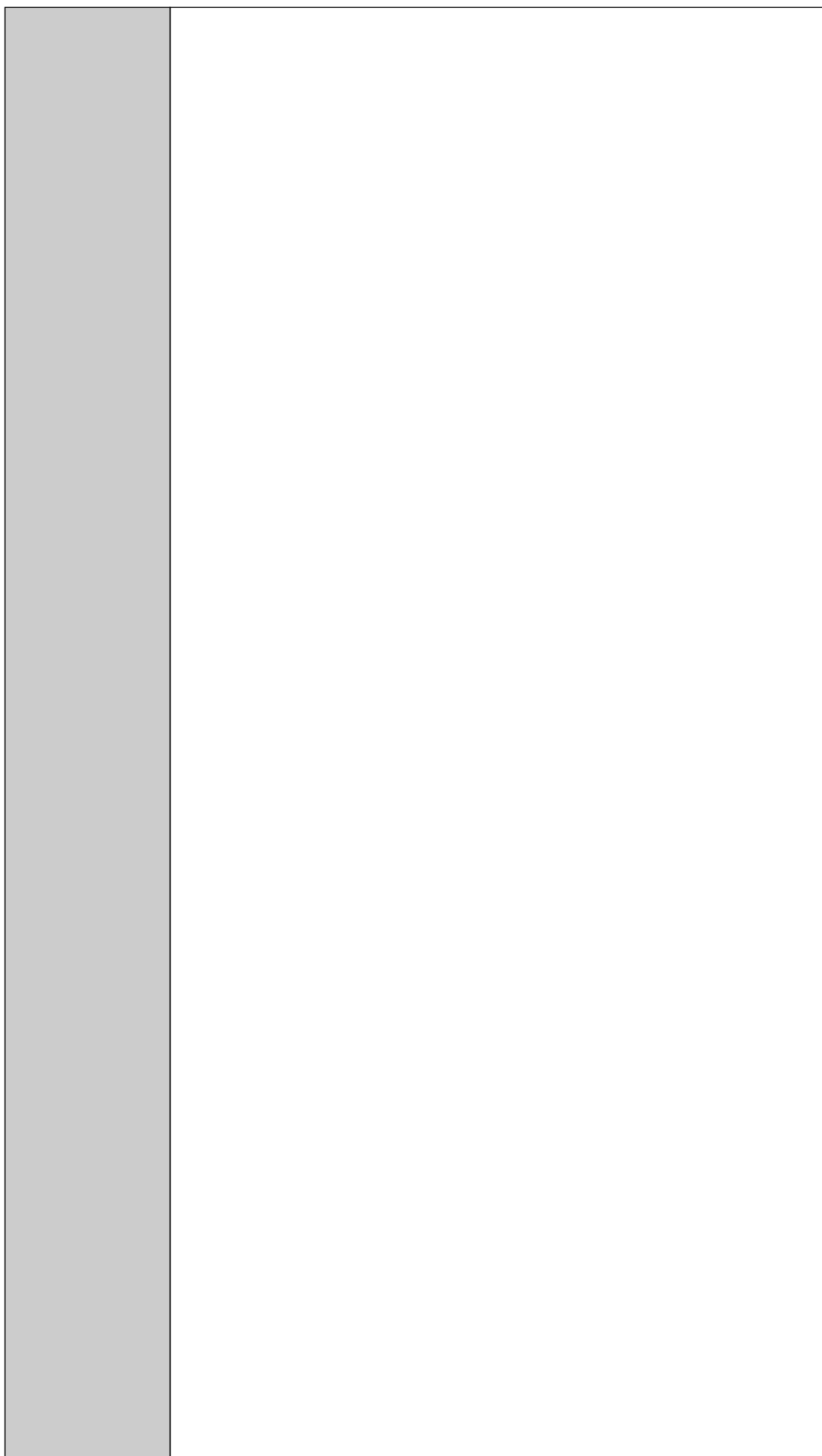
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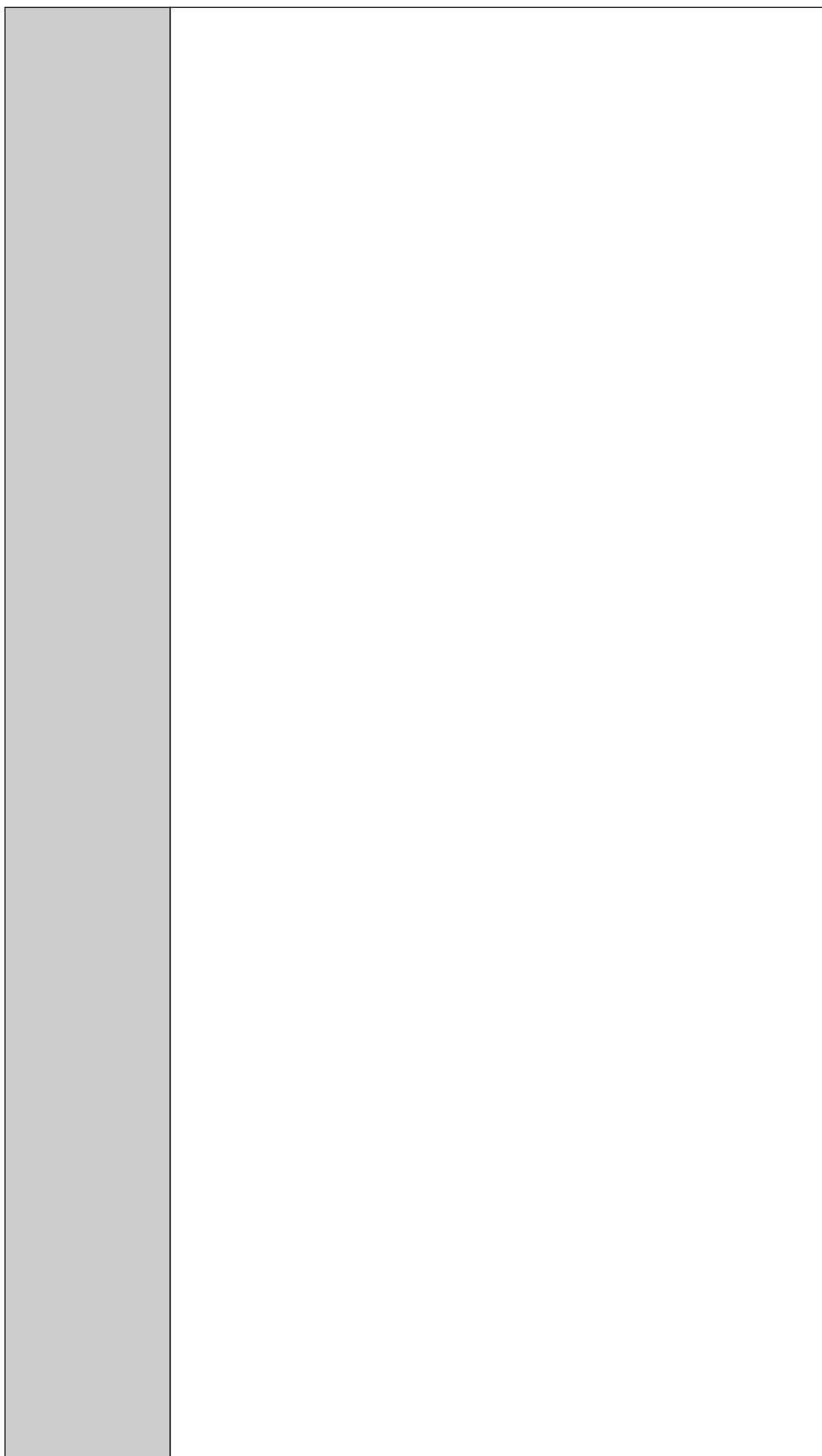
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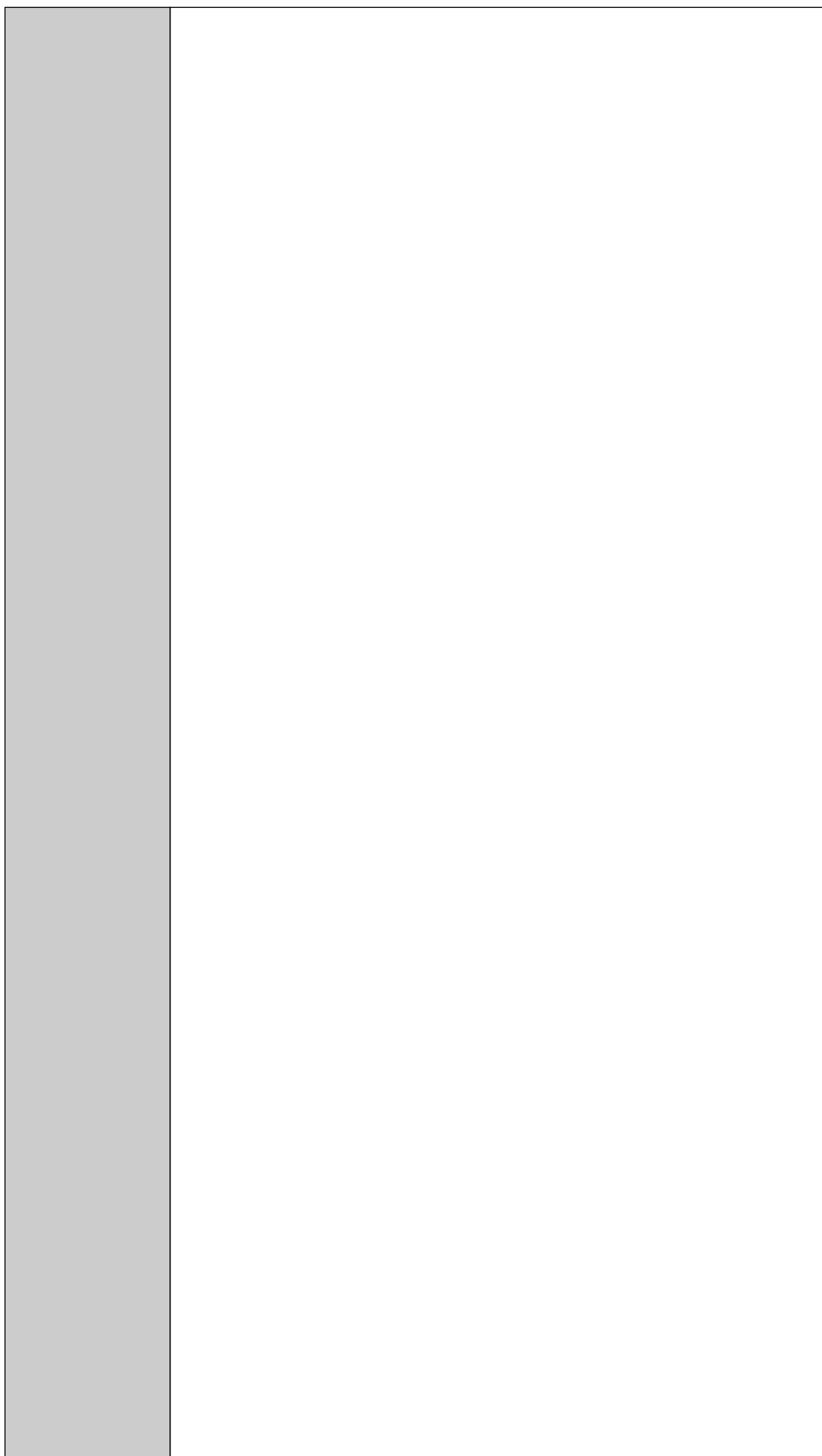
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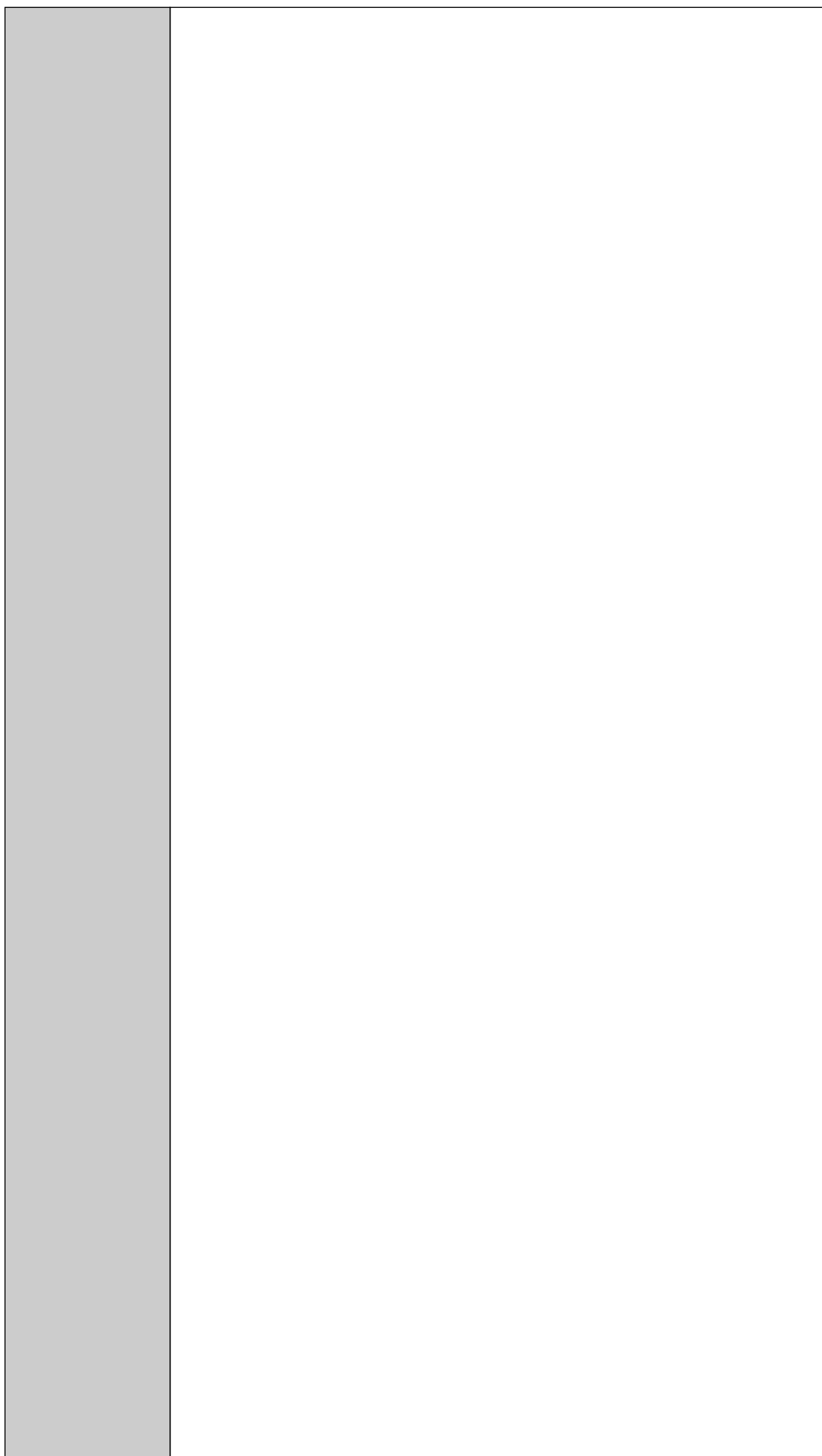
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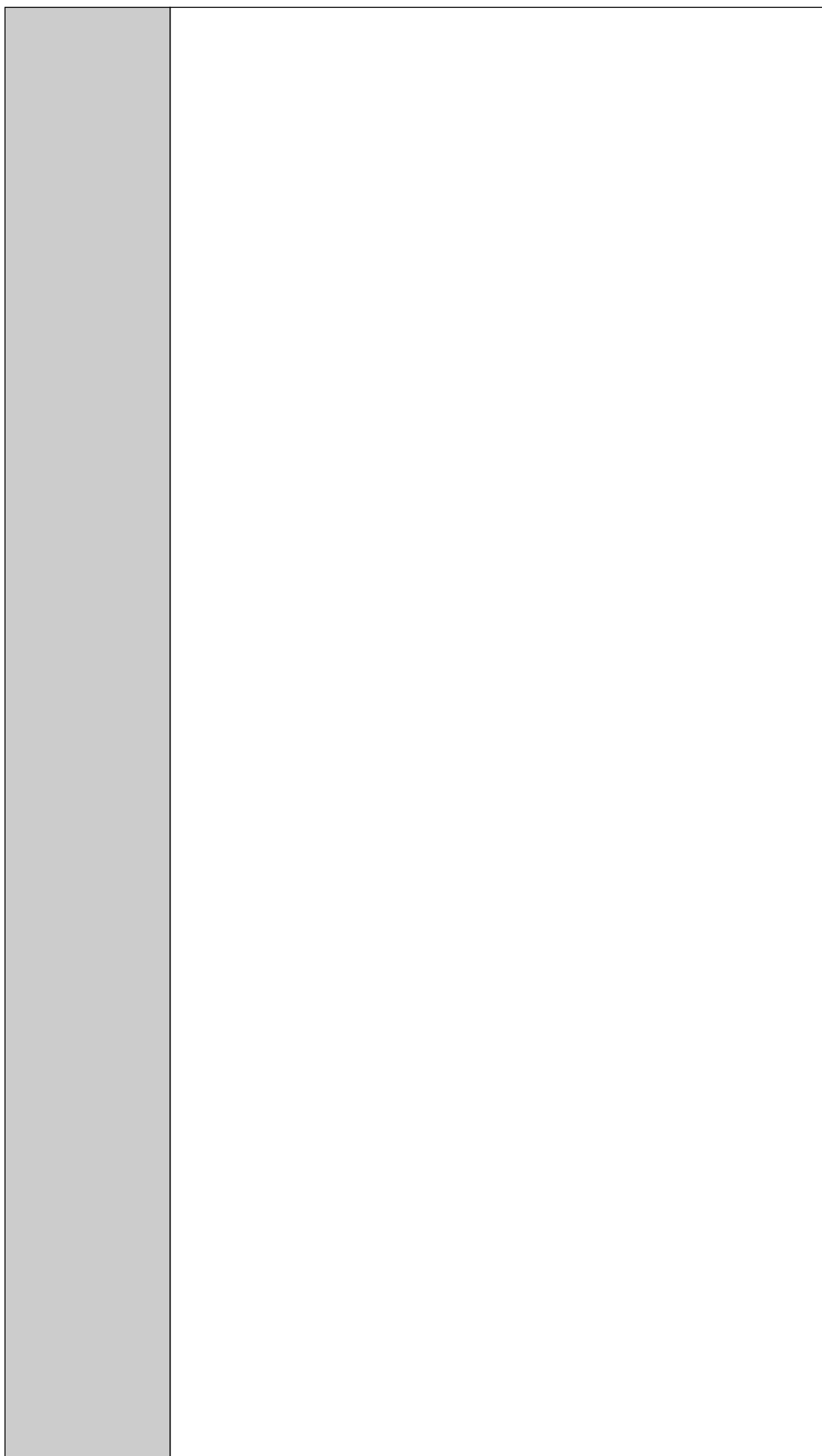
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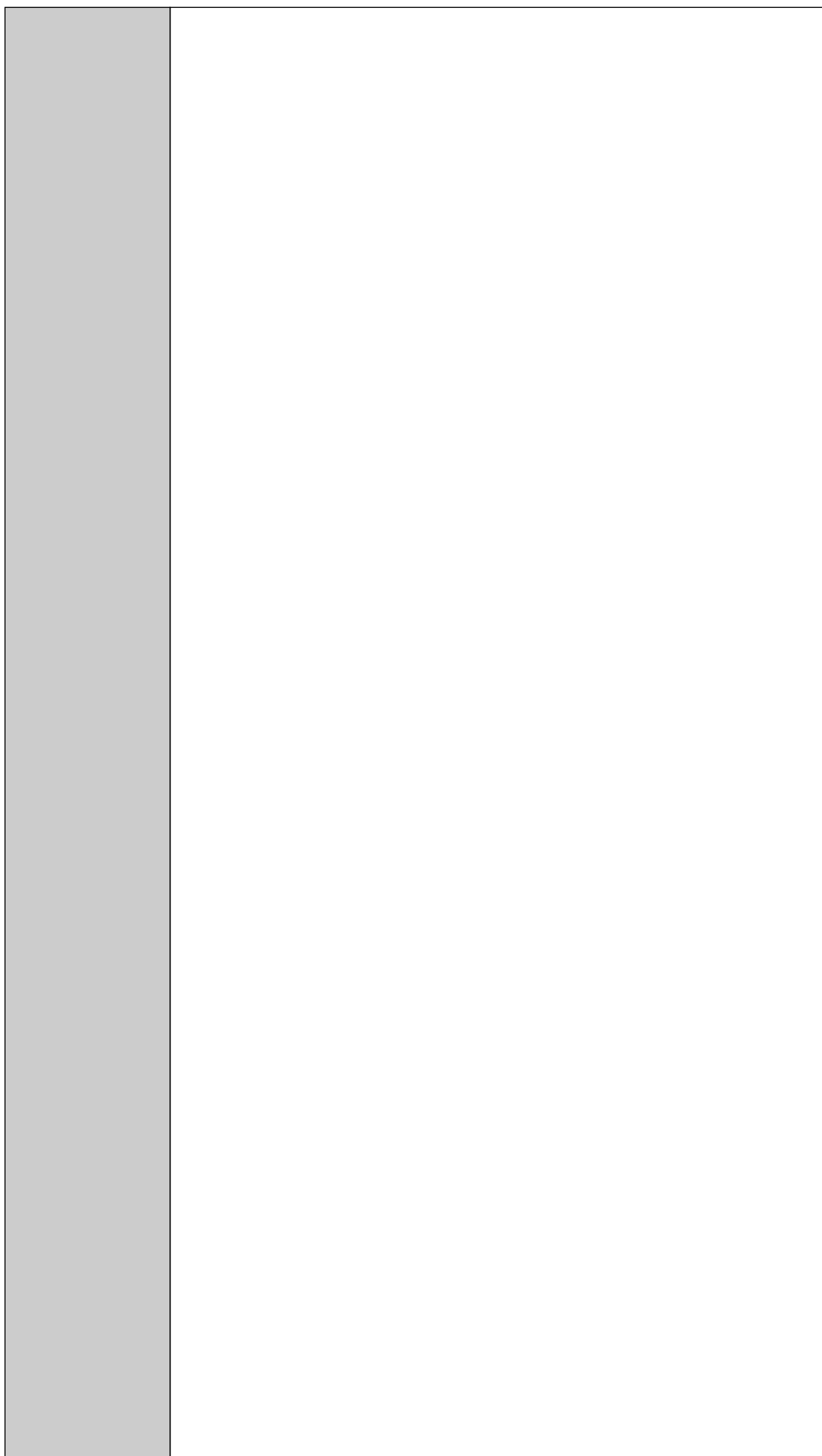
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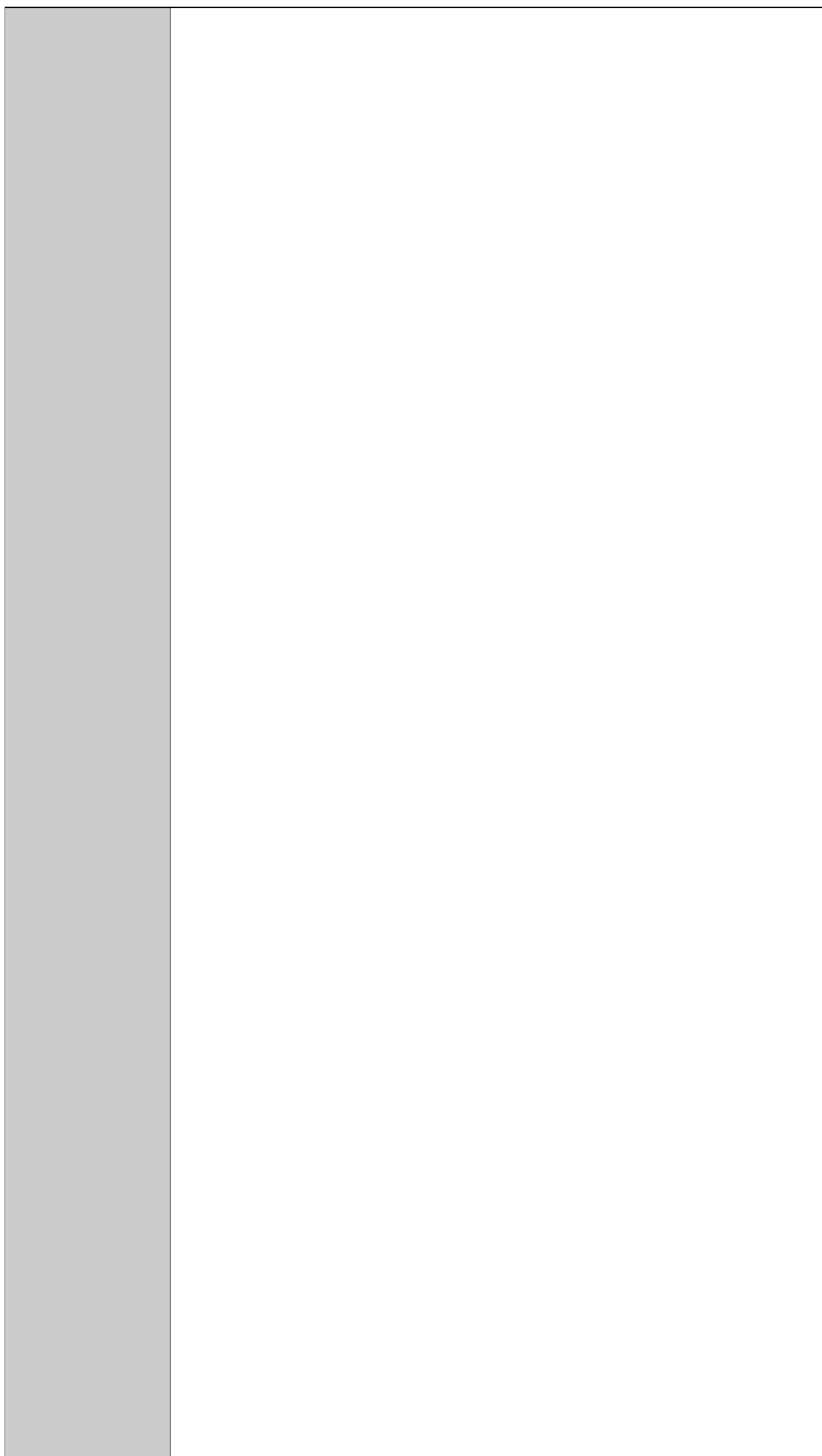
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Enrichment of Package Antenna Approach With Dual Feeds, Guard Ring, and Fences of Vias

Y. P. Zhang

Abstract—This paper enriches the package antenna approach to wireless modules by introducing the dual feeds, the guard ring, and fences of vias. The dual feeds enable the antenna for not only single-ended but also differential signal operations. The guard ring and fences of vias reduce the antenna backward radiation and improve the isolation between the antenna and radio chip. The design guideline of the guard ring and fence of vias for the package antenna approach is developed for the first time. An example antenna of this package approach using a microstrip patch radiator has been designed and fabricated in a low-temperature cofired ceramic (LTCC) technology for the wireless modules operating at the 5-GHz band. The antenna has a size of $17 \times 17 \times 2 \text{ mm}^3$ and contains the open cavity that is large enough to accommodate a radio chip of current size. Simulated and measured input impedance matching and far-field radiation properties are discussed. They show that the antenna achieves over 2.2% bandwidth while maintaining 90% efficiency.

Index Terms—Low-temperature cofired ceramic (LTCC) technology, microstrip antenna, wireless communications.

I. INTRODUCTION

THE popularity of the wireless enabled products such as laptop computers, mobile phones, and personal digital assistants has led to an increasing demand for wireless modules. Various antenna solutions have been proposed for wireless modules [1]–[4]. Among them, the chip antenna solution currently dominates. Chip antennas are surface-mountable and employ the dielectric loading techniques to miniaturize their size [5]. The dielectric materials are often ceramics with high permittivity and low-temperature cofired ceramic (LTCC) technology is widely used for manufacturing chip antenna in large quantity.¹ Chip antennas are assembled with integrated circuit chips on the same printed circuit boards as wireless modules. Obviously, the footprint of a chip antenna on the printed circuit board (PCB) impedes the further miniaturization of the wireless module in planar dimensions. To overcome the problems of the chip antenna solution and to better match with wireless modules, the package antenna approach has been recently proposed [6]–[12]. The package antenna approach deliberately explores the vertical dimension and implements the antenna as a cap to cover the wireless module. Zhang realized such an an-

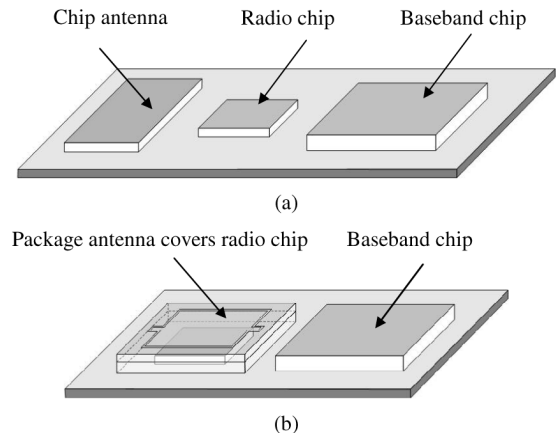


Fig. 1. (a) Chip antenna solution versus (b) package antenna approach.

tenna in a ceramic ball grid array package format and evaluated the effect of packaging elements on the performance of the antenna [7]. Ryckaert *et al.* implemented a circularly-polarized microstrip patch antenna and studied the codesign and assembly issues of a compact wireless module [8]. Wi, *et al.* designed a linearly-polarized microstrip stacked-patch antenna and investigated into the effects of fabrication tolerances and parasitics on the performance of the antenna [9], [10]. Lim and Leung and Gao *et al.* demonstrated linearly-polarized dielectric resonator antennas with circuit integration capability, respectively [11], [12].

In this paper, we enrich the package antenna approach to wireless modules by introducing the dual feeds, the guard ring, and fences of vias. The dual feeds enable the antenna for not only single-ended but also differential signal operations. The guard ring and fences of vias reduce the antenna backward radiation and improve the isolation between the antenna and radio chip. We describe the package antenna approach in Section II. Based on an LTCC technology, we develop the design guideline of the guard ring and fences of vias for the package antenna approach in Section III and design a specific package antenna for the wireless modules at the 5-GHz band in Section IV. Finally, we draw the conclusions in Section V.

II. PACKAGE ANTENNA APPROACH

Currently, a wireless module is often designed with two integrated circuit chips. One chip is for radio function and the other is for the baseband process. With the advancements in microelectronic technology, a single-chip solution of wireless devices is emerging. Fig. 1 shows the package antenna approach to the wireless module with respect to the chip antenna solution. It is obvious that the package antenna approach is supe-

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¹<http://www.ltcc.de>

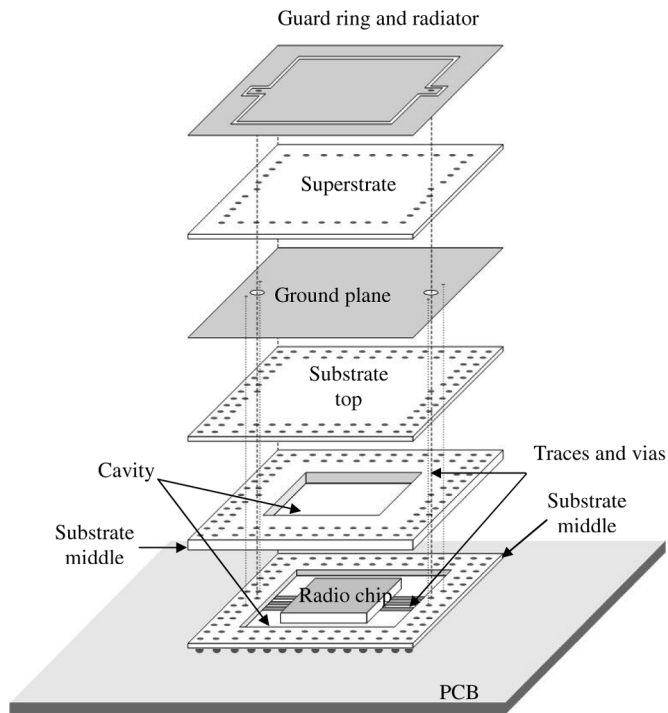


Fig. 2. Exploded view of package antenna approach.

rior to the chip antenna solution in the miniaturization of the wireless module in the planar dimensions. Of course, the vertical dimension of the wireless module will increase if the radio chip is a packaged chip. However, if the radio chip is a naked chip that can be directly mounted on the PCB using the chip on board (COB) techniques, the vertical dimension of the wireless module will not necessarily increase. Furthermore, the package antenna has much shorter distance to the radio-frequency (RF) output of the radio chip than a conventional chip antenna. This implies a smaller transmission loss.

Fig. 2 shows the exploded view of the package antenna approach. Above the ground plane is the superstrate of laminated dielectric layers. The radiator and guard ring are printed on the top surface of the superstrate. The radiator may take any form of a printed antenna. The guard ring is shorted to the ground plane with a fence of vias to reduce the antenna backward radiation. Below the ground plane is the substrate of laminated dielectric layers. The bottom surface of the top laminated layers of the substrate can be used to realize the band select filter [13], [14]. An open cavity is formed in the middle and bottom laminated layers of the substrate to encapsulate the radio chip on the PCB of a wireless module. The passive elements for the matching and bandwidth enhancement can be embedded in the middle and bottom laminated layers of the substrate. The substrate also contains fences of vias to further protect the radio chip from the backward radiation of the antenna and to connect the package antenna to the PCB of the wireless module. Fig. 2 also shows the radio chip mounted on the PCB. The radio chip is connected to the radiator through two feeding networks. A feeding network includes three signal traces on the PCB and three vias in the package antenna in the ground–signal–ground fashion. The

radio chip is shielded from the radiator by the ground plane and the fences of vias.

In highly integrated radio design, differential circuits are employed because they can reduce local oscillator feedthrough and leakage and to achieve higher linearity, lower offset and better immunity to common-mode noise due to power supply variations or substrate coupling. Both chip antenna solution marketed by the antenna industry and package antenna approach developed in the university laboratories are designed with a single feed. They are suitable for single-ended circuits and cannot be directly connected to modern radio chips. Baluns are required to connect the single-ended antenna to the differential circuits in the radio chip of a wireless module. As shown in Fig. 2, the package antenna approach is enriched in this work by introducing the differential antenna with dual feeds. Thus, the bulky and lossy baluns are not needed any more, which will not only translate into the reduction of bill of materials but also, more importantly, the improvement of the receiver noise performance and transmitter power efficiency of the radio chip.

The package antenna excites not only wanted space wave but also unwanted surface wave. The propagation of surface wave and backward radiation of both space and surface waves causes undesirable coupling between the antenna and the radio chip, thus degrading the performance of the wireless module. A few techniques are available to improve the isolation between the package antenna and the radio chip. The most effective technique is to use a shielding can. Unfortunately, it is usually difficult for most printed-circuit technologies to realize such a can structure. Recently, a sophisticated technique that features an electromagnetic bandgap (EBG) structure shows promising [15]. However, an effective EBG structure takes up a considerable space. It is known that the technique using guard ring and fence of vias is effective to improve the isolation and to reduce undesirable coupling in integrated circuit and package designs², [16]. Hence, we had conjectured that this technique could be used in our package antenna approach to improve the isolation. Later, we realized that the design guidelines of the guard ring and fences of vias developed for integrated circuits and packages could not be directly applied to the package antenna approach because the efficient radiation of the antenna should be maintained. Hence, it is worthwhile developing the design guideline of the guard ring and fence of vias for the package antenna approach. It should be noted that if the guard ring, the fence of vias, and the ground plane of the package antenna approach are designed properly, it creates a stable electromagnetic environment for the radiator; as a result, the detuning of the operating frequency of the radiator by the PCB board and other components in the wireless module is minimized.

III. DESIGN GUIDELINE OF PACKAGE ANTENNA

The design of the package antenna must consider its fabrication in large quantity, which requires novel manufacturing technologies. LTCC technology that uses noble metals and specific ceramic materials and has the flexibility in realizing an arbitrary

²<http://www.commsdesign.com/showArticle.jhtml?articleID=192200561>

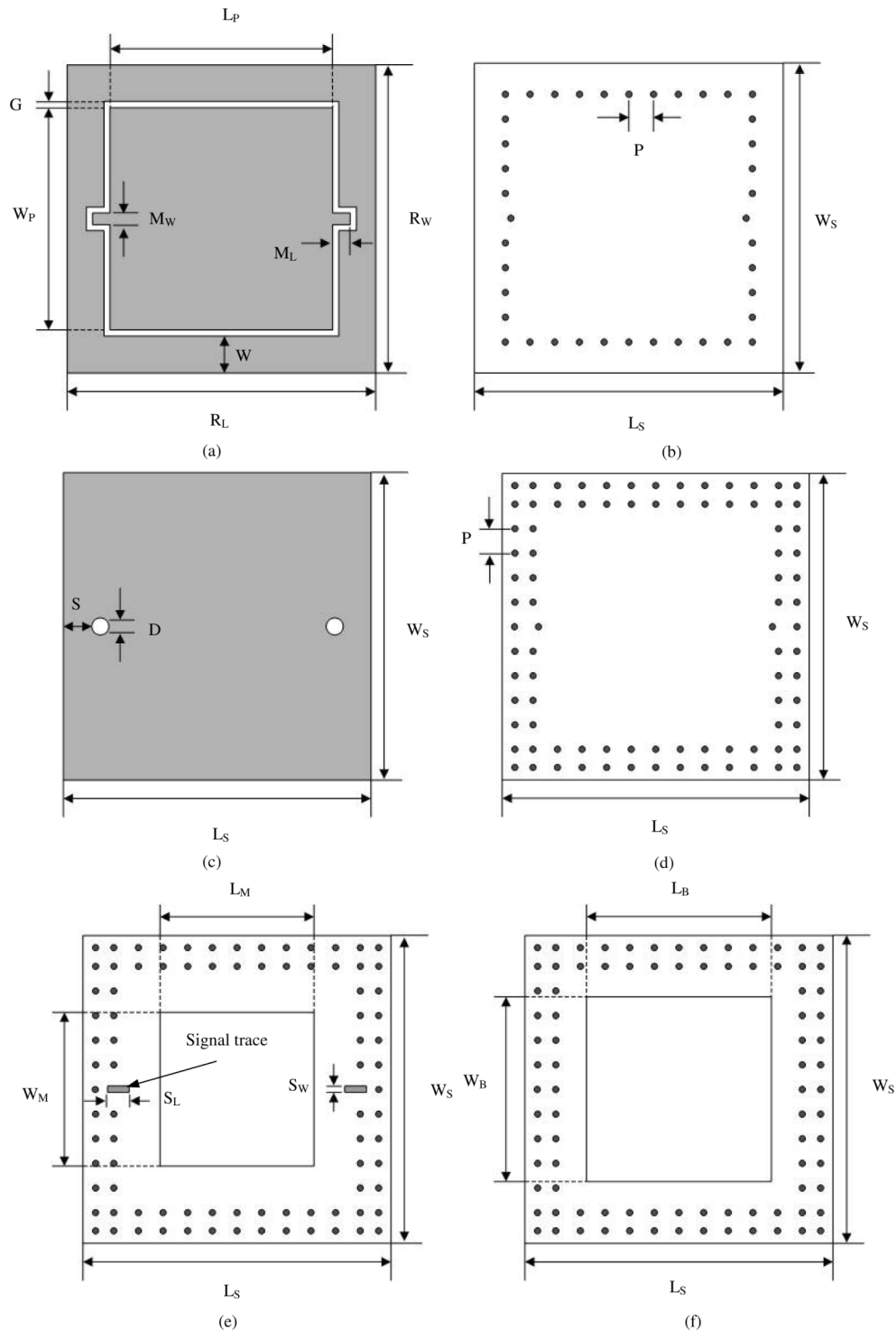


Fig. 3. Geometries and design parameters of laminated layers of the package antenna: (a) metallic radiator, (b) superstrate of laminated ceramic layers, (c) metallic ground plane, (d) substrate top of laminated ceramic layers, (e) substrate middle of laminated ceramic layers, and (f) substrate bottom of laminated ceramic layers.

number of metallic and ceramic layers is suitable for the mass production of the package antenna. There are a few LTCC material systems in the market. The LTCC material system from Ferro is used in this development. The physical layout rules are obeyed.³ The Ferro A-6 ceramic type has a dielectric constant of 5.9 and a loss tangent of 0.002 at 5 GHz. Two metallization

options are available: silver and gold, of which silver metallization is chosen for cost reason.

Fig. 3 shows the detailed geometries and design parameters of laminated layers of the package antenna. Typically, a metallic layer is 10 μm thick and a ceramic layer is either 100 or 200 μm thick. It is seen from Fig. 3(a) that the radiator is a differential microstrip patch antenna. The microstrip patch antenna

³<http://www.simtech.a-star.edu.sg/index-research.html>

is widely used in the package antenna approach [6]–[10] because it helps to spread heat generated by the wireless module. In Fig. 3(b), two feeding vias can be seen offset inwards with respect to the fence of vias that shorts the guard ring to the ground plane. The two holes on the ground plane in Fig. 3(c) are for the two feeding vias to pass through. There are two fences of vias through the substrate as shown in Fig. 3(d)–(f) that connect the ground plane to the wireless module ground on the PCB to improve the isolation. In Fig. 3(e), the capacitance of the signal traces is used to compensate the inductance of the feeding vias for matching and bandwidth enhancement. The openings in Fig. 3(e) and (f) are used to form the cavity.

The input impedance Z_d of the differential microstrip patch antenna is given by [16]

$$Z_d = 2(Z_{11} - Z_{21}) = 2(Z_{22} - Z_{12}) \quad (1)$$

where the Z parameters are defined at the driving points and they can be easily calculated with the cavity model and electromagnetic simulator [17]. The value of Z_d is required in the design of matching network between the antenna and the differential active circuitry in a radio system. The return loss calculated from Z_d is given by

$$\text{RL(dB)} = -20 \log \left(\left| \frac{Z_d - Z_c}{Z_d + Z_c} \right| \right) \quad (2)$$

where Z_c is 100 Ω .

Three important parameters are used to develop the design guideline of the guard ring and fence of vias for the package antenna approach. They are the guard ring width W , the gap between the guard ring and the microstrip patch radiator G , and the pitch of vias P . For most commercial LTCC to be reliable for mass production, the width W , the gap G , the diameter of via, and the difference between the pitch P and the diameter of via should be equal to or larger than 100 μm . The guard ring and fence of vias are used mainly to reduce the antenna backward radiation. Without the guard ring and fence of vias, the diffraction of surface wave at the edges of the ground plane would significantly enhance the coupling or deteriorate the isolation between the antenna and the radio chip.

First, let determine the guard ring width W . Considering the guard ring, fence of vias, and the ground plane as a transmission line, one can easily find out that the effective reduction of surface wave requires the width W being

$$W = \frac{\lambda_0}{\alpha \sqrt{\epsilon_r}} \quad (3)$$

where α is 2 or 4 for the fence of vias located along the middle line of the guard ring or along the outer edge of the guard ring, λ_0 is the operating wavelength, and ϵ_r is the dielectric constant. It is found that the fence of vias should be located at the outer edge of the guard ring to have a smaller width as that used to realize the soft-surface structure [18]. However, even so, the width W is still too larger for the wireless module operating at the 5-GHz band. Thus, the value for the width W should be reduced but must be larger than the minimum width limited by

TABLE I
PACKAGE ANTENNA GEOMETRICAL PARAMETER VALUES

	Dimensions	Remarks
Patch	WP \times LP = 10.5 \times 10.5 mm ²	10 μm thick
Line	MW \times ML = 1 \times 3 mm ²	10 μm thick
Superstrate	17 \times 17 \times 1.0 mm ³	5 ceramic layers
Ground plane	17 \times 17 mm ²	10 μm thick
Substrate top	17 \times 17 \times 0.4 mm ³	2 ceramic layers
Cavity	WM \times LM = 7 \times 7 mm ²	2 ceramic layers
	WB \times LB = 10 \times 10 mm ²	1 ceramic layer
Signal trace	SW \times SL = 1 \times 3 mm ²	10 μm thick
Hole	S = 2 mm and D = 0.5 mm	10 μm deep

the physical layout rule. The degradation due to the reduction of the guard ring width on the isolation level can be compensated by introducing additional fence (or fences) of vias in the substrate, as shown in Fig. 3(d)–(f).

Then, let determine the gap G . It is obvious that the gap G affects the radiation. The gap G should be larger enough to yield an efficient radiation. It is found that the gap G should be

$$G \geq \Delta \quad (4)$$

where Δ signifies the extension of the fringing field and is given by

$$\Delta = 0.412H \frac{(\epsilon_{\text{eff}} + 0.3) \left(\frac{W_p}{H} + 0.264 \right)}{(\epsilon_{\text{eff}} - 0.258) \left(\frac{W_p}{H} + 0.8 \right)} \quad (5)$$

In (5) H is the height of the guard ring from the ground plane, W_p is the microstrip patch width, and ϵ_{eff} denotes the corresponding effective dielectric constant, and is related to ϵ_r , as follows:

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{H}{W_p} \right)^{1/2} \quad (6)$$

Finally, for the pitch of vias P , it should ideally be zero to form a wall rather than a fence. Realistically, it should be chosen to satisfy

$$P \frac{\sqrt{\epsilon_r}}{\lambda_0} \leq \frac{1}{10} \quad (7)$$

together with

$$\frac{H \sqrt{\epsilon_r - 1}}{\lambda_0} < \frac{1}{4} \quad (8)$$

It should also be known that the minimum pitch is limited by the physical layout rule. The design guideline given in (3)–(8) can be easily modified for conventional printed antennas fabricated with other technologies.

IV. SPECIFIC PACKAGE ANTENNA

Having developed the design guideline, we now proceed to design a specific package antenna. The design of the package antenna must also consider the automatic assembly of the package antenna to the printed circuit board. In this regard, the package antenna should be designed as the JEDEC standard compliant. The package antenna was designed to have a standard body size

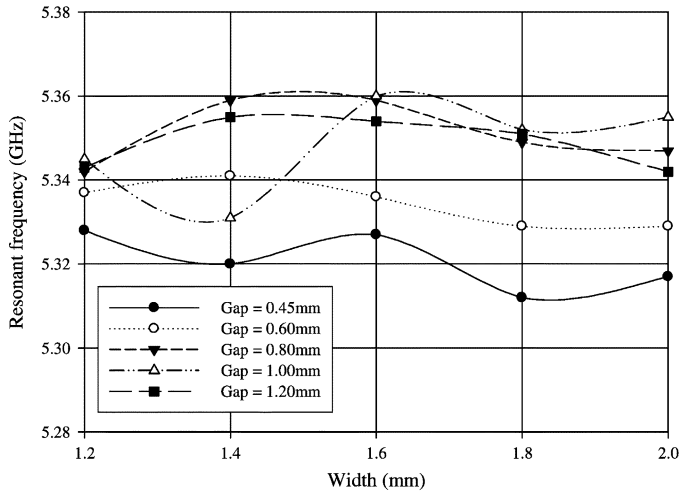


Fig. 4. Simulated resonant frequency of the antenna as a function of the guard ring width and the gap.

$17 \times 17 \times 2 \text{ mm}^3$. The size of the microstrip patch was first estimated with the CAD formula to operate at the TM_{01} mode and then adjusted from the HFSS simulation [17]. Table I shows the values of the geometrical parameters of the package antenna for operation at 5.3 GHz. The radiator of the package antenna is a square microstrip patch. The cavity is a stepped space large enough to accommodate a radio chip of current size. The guard ring width, the extension of the fringing field, and the pitch of vias calculated from (3), (5), and (7) are $W = 5.8 \text{ mm}$, $\Delta = 0.45 \text{ mm}$, and $P \leq 2.3 \text{ mm}$, respectively. It is obvious that the guard ring width $W = 5.8 \text{ mm}$ is not practical for this design. A realistic guard ring width is up to 2.0 mm for this design in LTCC.

Fig. 4 shows the simulated resonant frequency of the antenna as a function of the guard ring width W and the gap G , respectively. It is seen that the grounded guard ring slightly shifts up the resonant frequency of the antenna. This is because the electric fields are terminated on the guard ring instead of on the ground plane which reduces the effective permittivity of the dielectric material [15]. The frequency shift can be compensated by a simple scaling of the patch length [19].

As expected, the grounded guard ring reduces the antenna backward radiation and improves the isolation between the antenna and radio chip. Based on our simulations for the guard ring width varying from 1.2 to 2 mm and the gap from 0.45 to 1.2 mm, it is observed that a 3-dB reduction in the backward radiation or a 3-dB improvement in the isolation can be achieved. However, the achievement is made with some bandwidth penalty. It is found that the impedance bandwidth decreases 5~7% and the wider the guard ring is and the larger the gap is, the smaller the decreasing amount is. It is also found that the grounded guard ring yields very little effect on the broadside radiation and the peak gain remains almost unchanged because the design guideline has ensured that the fringing field is not disturbed.

Considering the dicing requirement in LTCC fabrication, we chose the guard ring width W parallel to the radiating edges to be 1.6 mm and parallel to nonradiating edges to be 1.4 mm, the

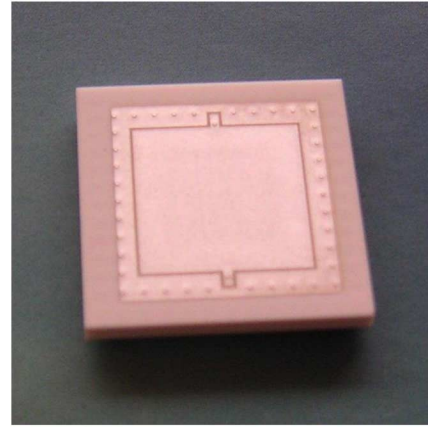


Fig. 5. Photo of the fabricated package antenna in LTCC.

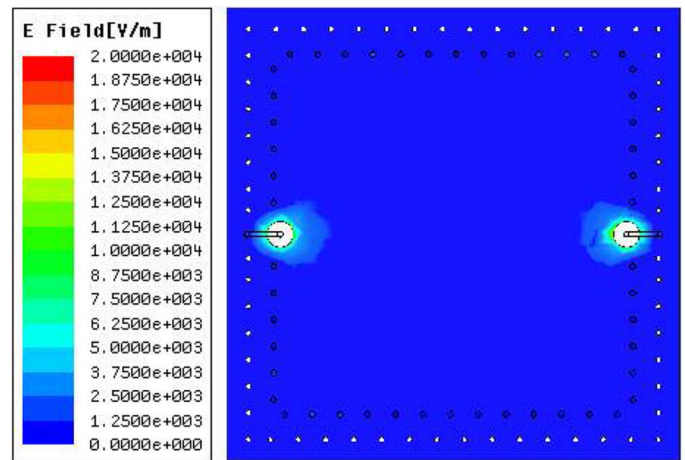


Fig. 6. Simulated electric field density on the PCB ground.

gap G to be 0.45 mm and the via pitch P to be 1.27 mm in our design, respectively. Fig. 5 shows the photo of the fabricated package antenna. The package antenna was mounted on a PCB for testing. The size of the PCB was $60 \times 40 \times 0.8 \text{ mm}^3$.

Fig. 6 shows the simulated electric field density on the bottom surface of the package antenna ground plane. Note that the fences of vias provide an efficient grounding connection from the package antenna ground to the PCB ground and the electric field from the antenna backward radiation is rather weak inside the cavity. The isolation between the antenna and radio chip is guaranteed.

The package antenna was tested with a balun and an HP 8510C network analyzer in the anechoic chamber. Fig. 7 compares the simulated and measured return loss of the package antenna. The return loss indicates how well the antenna is matched to a signal source and how wide the impedance bandwidth is. It is seen that the simulated and measured return loss are in acceptable agreement. The measured resonant frequency shifts up from the designed 5.34–5.36 GHz because the LTCC shrinkage was not accurately controlled in fabrication. The difference in the return loss values is caused by the balun. The amplitude and phase imbalance of the balun can not be calibrated. The return loss above 10 dB at the frequency of operation indicates acceptable matching between the antenna and the 100- Ω source is

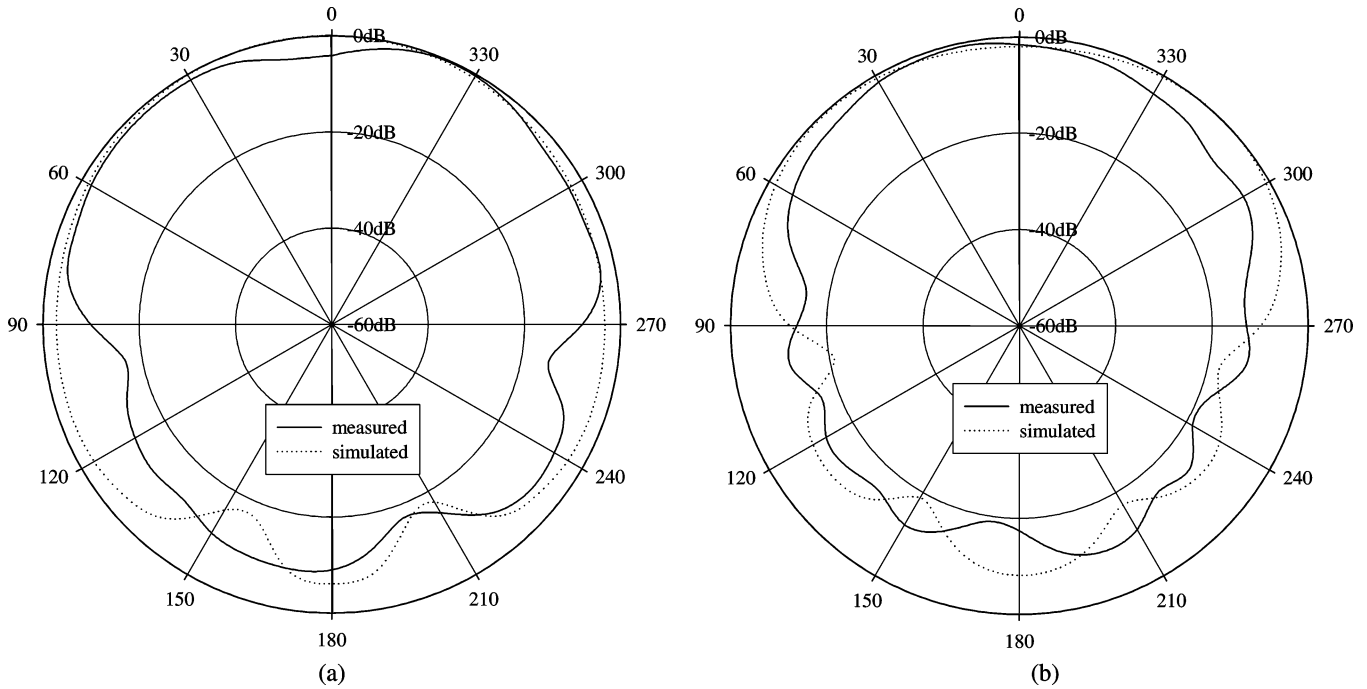


Fig. 8. Radiation patterns of the package antenna: (a) E-plane and (b) H-plane.

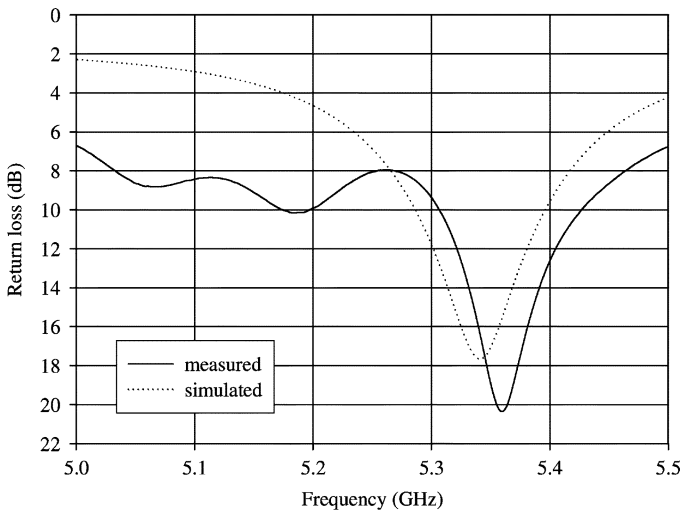


Fig. 7. Return loss of the package antenna.

achieved. The measured impedance bandwidth of the differential antenna is 120 MHz ($0.11/5.36 = 2.2\%$). The 2.2% relative bandwidth is enough for the WLAN system operating at 5.775 GHz. However, it is not enough for the WLAN system operating at 5.25 GHz. The bandwidth of the differential microstrip patch antenna should be enhanced for more applications.

Fig. 8 compares the simulated and measured copolar radiation patterns of the differential antenna at 5.36 GHz. It can be observed that the simulated radiation patterns agree reasonably with the measured radiation patterns. There are some discrepancies, which, we believe, are caused by the existence of the balun and its amplitude and phase imbalance in the measurements. The radiation is stronger in the upper hemisphere, i.e., in the direction normal to the microstrip patch. As the square microstrip patch radiator was used, the cross-polar radiation should

TABLE II
MEASURED PERFORMANCES OF THIS PACKAGE ANTENNA AND OTHER REPORTED DESIGNS

Reference	Volume mm ³	Frequency GHz	Bandwidth MHz	Gain dBi
[4]	20 × 20 × 0.8	5.8	200	4.5
[7]	20 × 20 × 1.3	5.48	100	4.8
[9]	23 × 23 × 3.5	5.25	400	6
[10]	10.3 × 10.3 × 2.0	5.85	180	4.98
[11]	10.3 × 10.3 × 1.3	5.48	100	-0.17
[12]	25 × 25 × 4.8	5.5	1150	6
This work	17 × 17 × 2	5.36	120	3.2

be strong. However, it was found that the cross-polar radiation was about 10 dB lower than the copolar radiation in the broad-side direction. The lower cross-polar radiation is the result of the differential signal operation. The antenna efficiency was calculated to be 90%. The antenna peak gain was found to be 3.2 dBi, which is higher than gain of most conventional dielectric chip antennas.

Finally, we list key data of this work with other package antenna designs in Table II. We have no intention to compare them because it is difficult to make a fair comparison between the different solutions since they are fabricated in different technologies and with different sizes.

V. CONCLUSION

This paper has greatly enriched the package antenna approach to wireless modules by introducing the dual feeds and electromagnetic fences. The dual feeds enable the antenna for not only single-ended but also differential signal operations. The guard ring and fences of vias reduce the antenna backward radiation and improve the isolation between the antenna and radio chip. The design guideline of the guard ring and fences of vias was

developed for the package antenna approach for the first time. An example antenna of this package approach has been designed and fabricated in an LTCC technology for the wireless modules operating at the 5-GHz band. The antenna had a size of $17 \times 17 \times 2 \text{ mm}^3$. Simulated and measured input impedance matching and far-field radiation properties were discussed. The antenna achieved over 2.2% bandwidth while maintaining better than 90% efficiency.

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